Maximal punching performance in amateur boxing:

An examination of biomechanical and physical performance-related characteristics

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By **Edward Stanley**

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The material being presented for examination is my own work and has not been submitted for an award of this or another HEI except in minor particulars which are explicitly noted in the body of the thesis. Where research pertaining to the thesis was undertaken collaboratively, the nature and extent of my individual contribution has been made explicit.

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Abstract

Punches in boxing are intricate actions requiring the coordinated and synergistic recruitment of leg, trunk and arm musculature. Maximal punches can have a marked impact on the outcomes of boxing contests. Currently, there is an absence of research appraising the biomechanics and physical performance-related qualities associated with boxing punches, and as such, there are no practical guidelines pertaining to resistance training and its impact upon these important characteristics. In this respect, coaches and boxers are reliant consequently upon non-scientific approaches to training and contest preparation. Thus, the purpose of this thesis was to quantify the biomechanics and physical performance-related qualities associated with maximal punching techniques common to amateur boxing, and investigate the extent to which resistance training enhances such features.

Study 1 quantified the three-dimensional kinetics and kinematics of maximal punches common to boxing competition to identify the differences between punch types (straights, hooks, and uppercuts), whilst Study 2 investigated the movement variability of these measures across punch types. These studies revealed significant differences for the majority of kinetic and kinematic variables between punch types. High within-subject, between-subject, and biological variability were recorded for the same variables across punch types, independent of the amount of boxing experience. These findings confirm that kinetic and kinematic characteristics vary from punch to punch, with boxers appearing to manipulate kinematic variables in order to achieve a consistent intensity and end-product. Study 3 quantified the relationships between physical performance-related traits and kinetic and kinematic qualities of maximal punches, and revealed moderate-to-large associations with muscular strength and power. From this, Study 4 appraised the extent to which strength and contrast resistance training enhanced maximal punch biomechanics and physical performance-related qualities. The findings highlighted that contrast training was superior among male amateur boxers over a six-week intervention, though strength training alone also brought about improvements.

This current research has advanced our understanding of maximal punching and the influence of resistance training on a variety of its determinants. Nonetheless, future research is required to identify if the same findings can be generalised to higher standards of boxing and whether alternative strength and conditioning strategies are equally, or more effective.

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Abbreviations

1RM	One-repetition maximum
2D	Two-dimensional
3D	Three-dimensional
ABA	Amateur Boxing Association
ABAE	Amateur Boxing Association of England
AIBA	Association Internationalé de Boxe Amateur (Amateur International Boxing Association)
Akt-mTOR-S6K	Akt/protein kinase B-mammalian target of rapamycin-p70 S6 kinase
AMPK-PGC-1	Adenosine monophosphate-activated kinase-peroxisome proliferator activated receptor gamma coactivator-1
ANOVA	Analysis of variance
APS	Actions per second
ASCII	American Standard Code for Information Interchange
BC	Before Christ
BP	Bench press
BS	Back squat
BT	Ballistic training
CI	Confidence interval
CMJ	Countermovement jump
cm	Centimetres
CoM	Centre of mass
CoP	Centre of pressure
CT	Contrast training
CV%	Coefficient of variation
d	Cohen’s *d* (effect size)
deg/s	Degrees per second
DT	Delivery time
EJAV	Elbow joint angular velocity

EJAV%	Timing of elbow joint angular velocity (percent)
EMG	Electromyography
ES	Effect size
F_{max}	Maximal force
FV	Fist velocity
F-V	Force-velocity relationship
g	Grams
g	Gravitational acceleration
GRF	Ground reaction force
GTO	Golgi tendon organ
HBD	Hexagonal bar deadlift
Hz	Hertz
ICC	Intraclass correlation coefficients
Imp	Impulse
in	Inch
Kg	Kilograms
LoA	Limits of agreement
LLFyI	Lead leg net braking impulse
LLFzI	Lead leg vertical impulse
LLGRF	Lead leg ground reaction force
LWC%	Large worthwhile change %
m	Metres
min	Minutes
mm	Millimetres
MMA	Mixed martial arts
ms	Milliseconds
m/s	Metres per second
m/s^2	Metres per second squared
MIF	Maximum isometric force

MPP	Mean propulsive power
MV	Movement variability
MWC%	Moderate worthwhile change %
mTOR	Mechanistic/mammalian target of rapamycin
MTU	Muscle Tendon Unit
N	Newton
N/kg	Newtons per kilogram
N/s/kg	Newtons per second per kilogram
N·m	Newton metre
OL	Olympic weightlifting
PGC-1	Peroxisome proliferator-activated receptor gamma coactivator-1
P_{max}	Maximum power
PT	Plyometric training
QTM	Qualisys Track Manager
r	Pearson product-moment coefficient
R^2	Coefficient of determination
rad/s^2	Radians per second squared
RFD	Rate of force development
RLFyI	Rear leg net propulsive impulse
RLFzI	Rear leg vertical impulse
RLGRF	Rear leg ground reaction force
RT	Resistance training
RT-SEP	Resistance training-induced sub-optimisation on endurance performance
SD	Standard deviation
SEM	Standard error of measurement
SJ	Squat jump
SJAV	Shoulder joint angular velocity
SJAV%	Timing of shoulder joint angular velocity (percent)

SSC	Stretch-shortening cycle
ST	Strength training
SWC%	Smallest worthwhile change %
TE	Typical error
V_{max}	Maximal velocity
W/kg	Watts per kilogram

Chapter 1

Introduction

1.1. Research Overview

Amateur boxing is a combat sport involving short duration, high-intensity offensive and defensive manoeuvres, interspersed with short recovery periods (Khanna & Manna, 2006; Smith, 2006). Competition within the sport, governed by the Amateur International Boxing Association (AIBA), encompasses weight-restricted full-contact combat with the fists between two opponents. Boxing bouts are usually contested over three rounds, each two to three-minutes in duration, divided by one-minute rest intervals. Competitions within the United Kingdom are sanctioned by the Amateur Boxing Association (ABA) at regional and national level whilst international bouts, including those staged at the summer Olympic Games, are sanctioned by the AIBA.

The intention during competition is to outperform or ‘knock-out’ an opponent through the implementation of clean punching techniques to the head or torso. Performances are scored at the end of each round by the collective impressions of five judges using a 10-point must-system (in which the winner of the round receives 10 points whilst the other competitor receives nine or less). A boxer’s overall score per round is based upon the number of ‘quality’ blows landed to the target area (head and torso), domination of a bout via technical and tactical superiority and competitiveness (AIBA, 2017a). However, the most desirable conclusion to a contest is to knock-out the opponent, ensuring a win (Mack, Stojsih, Sherman, Dau, & Bir, 2010). A knock-out is achieved if one boxer is unable to continue competing as a result of punches administered by the opponent.

Despite amateur boxing’s standing as an Olympic event with global popularity (201 affiliated nations - AIBA, 2017b), there is a surprising dearth of performance-related scientific research. With competitive international-level boxing characterised by high-intensity efforts incorporating ~1.55 actions per second (APS), ~21 punches, ~3.6 defensive movements and ~56 vertical hip movements (Davis, Connorton, Driver, Anderson, & Waldock, 2018) and national-level boxing by ~25 punches and ~10 defences per minute across 3 rounds (Thomson & Lamb, 2016), it seems logical its protagonists would benefit from interventions based on quantitative appraisals both of physical performance-related traits and movement demands, and the biomechanical factors that relate to the principal action of punching. That is, scrutiny of boxing's internal and external loads will be useful for developing conditioning programmes (Thomson & Lamb, 2017a; 2017b), whereas detailed analysis of punching could translate into specific training regimes designed to enhance a boxer's most effective actions.

The paucity of biomechanical data published in the boxing literature has concentrated on the kinematics (motion and velocity) of the upper-body limbs, focussing specifically on the hand, wrist and forearm (Cheraghi, Alinejad, Arshi, & Shirzad, 2014; Fuchs, Lindinger, & Schwameder, 2018; Kimm & Thiel, 2015; Piorkowski, Barton, & Lees, 2011: Viano et al., 2005; Walilko, Viano, & Bir, 2005). Moreover, some studies have measured the lower-body kinematics (Bingul, Bulgan, Tore, Aydin, & Bal, 2017), electromyography (EMG) (Dyson, Smith, Martin, & Fenn, 2007; Lockwood & Tant, 1997), and impact forces (Dyson et al., 2007; Loturco et al., 2016; Mack et al., 2010; Pierce, Reinbold, Lyngard, Goldman, & Pastore, 2006; Smith, Dyson, Hale, & Janaway, 2000; Viano et al., 2005; Walilko et al., 2005) of boxing punches.

Straight (jab and rear-hand cross) and hook (lead and rear) punches have been assessed as these particular strikes are the most common in amateur boxing bouts with Thomson and Lamb (2016) documenting ~64 jabs, ~39 rear-hand crosses, ~49 lead hooks and ~23 rear hooks over the duration of 9-minute male contests. Thomson and Lamb (2016) also reported on the uppercut (~5 lead uppercut; ~8 rear uppercut), punches considered to be fundamental and often most effective within the sport. Advancing the understanding of the kinematics of such punch techniques during performance could provide coaches and boxers expedient information regarding a boxer's technical proficiency and reveal potential interventions likely to enhance punching performance.

Though kinematic analyses can be useful in appraising sporting technique, research tends to also consider the forces (kinetics) of the actions performed. While numerous studies have assessed the impact force of different punches using wall-mounted force plates and dynamometers (Atha, Yeadon, Sandover, & Parsons, 1985; Dyson et al., 2007; Loturco et al., 2016; Mack et al., 2010; Smith et al., 2000; Viano et al., 2005; Walilko et al., 2005), kinetic analysis of a boxer's lower-body during such punches is limited to two studies (Mack et al., 2010; Yan-ju, Yi-gang, Yan, & Zheng-Ping; 2013) which both noted its important role to the biomechanical features (fist velocity and impact force) of punches. Still, further research is warranted, particularly involving ground reaction force (GRF), arguably the most important factor that influences maximal punching capabilities (Lenetsky, Harris, & Brughelli, 2013).

GRF assessments allow biomechanists to observe the magnitude of force produced and in what direction it is applied. Such assessments have been reported in other combat sports, such as taekwondo (Wasik, Santos, & Franchini, 2013), karate (Lechostaw, Oziewiecki, & Mączyński, 2005), kung fu and karate (Gulledge & Dapena, 2008) and jiu-jitsu (Oliveira, Moreira, Godoy, & Cambraia, 2006), but not in boxing. A better understanding of how force is being generated and the differences, for example, between lead and rear leg force production, and the direction(s) in which it is applied across different punch techniques could assist in the development of boxing-specific strength and conditioning strategies.

The variability of specific biomechanical qualities (impact kinetics) has also been reported in previously (Lenetsky, Brughelli, Nates, Cross, & Lormier, 2017), with experienced boxers exhibiting less movement variance than less experienced boxers. Research has presented contrasting views concerning movement variance (MV), with some authors reporting it as an undesirable quality indicative of dysfunctional movement patterns (Bartlett, 2007; Langdown, Bridge, & Li, 2012), while others have suggested how skilled-athletes purposely vary movements as a means of adapting their athletic performance to environmental and/or situational features of competition (Bartlett, 2007; Wagner et al., 2012). Though Lenetsky et al. (2017) identified the variability for punch impact kinetics, the extent of MV and its influence on the upper-body kinematics and lower-body kinetics of maximal punching are currently unknown. Consequently, quantifying MV could develop understanding of the consistency of specific biomechanical qualities from punch-to-punch, providing useful information to document performance changes following training interventions and/or practices.

Whilst the technique of punching is important, several papers have identified the importance of a boxer's physical and physiological abilities (Chaabene et al., 2015; Del Vecchio, 2011; Loturco et al., 2016). For example, Guidetti, Musulin, and Baldari, (2002) concluded that upper-body isometric muscular strength was a key determinant of boxing performance. Indeed, maximal punch force is dependent upon a boxer's muscular strength (Chaabene et al., 2015), power (Turner et al., 2011) and speed (Chang, Evans, Crowe, Zhang, & Shan, 2011) alongside their technical expertise. Moreover, physical attributes have been found to contribute as much as 56-65% to the variation in punching accelerations and 67-85% of impact forces observed across elite karate competitors and elite amateur boxers, respectively (Loturco et al., 2014; 2016). Most recently, Loturco et al. (2016) determined strength and power variables correlated with punching force in boxers, yet speed (Coulson & Archer, 2015) and acceleration (Adamczyk & Antoniak, 2010), thought to be imperative to punching performance, were not examined. Furthermore, contrary to Guidetti et al. (2002), poor relationships have been reported between isometric strength tests and dynamic sporting movements (Anderson et al., 1991; Coulson & Archer, 2015; James et al., 2016a; Rutherford & Jones, 1986; Wilson, Lyttle, Ostrowski, & Murphy, 1995). It is therefore clear further investigation into dynamic strength and power qualities in boxer's remains warranted.

Recognition of physical performance-related qualities influencing maximal punching performance is necessary to prepare boxers for the specific demands of competition and to reinforce correct movement mechanics (Piorkowski, 2009). Such physical qualities could be identified through physical tests and assessments of punching performance. Due to the lack of punch-specific physical and physiological profiles, when attempting to enhance punching ability boxing coaches are reliant upon methods of trial and error, meaning current boxing training methods are likely sub-optimal (Turner et al., 2011). As maximal punching necessitates a spectrum of physical and physiological qualities (Čepulėnas, Bružas, Mockus, & Subačius, 2011), understanding the specific components that primarily influence punching will inform boxers and coaches of the eminent training modality to consider. Furthermore, as the number of good quality punches landed on a target area is an essential component within the sport and an important judging criterion within competitive bouts (AIBA, 2017a), the need for further study of punching performance within boxing is evident.

Punches in boxing are intricate actions requiring the coordinated and synergistic recruitment of leg, trunk and arm musculature (Turner et al., 2011). As the most desired contest outcome is victory by way of knocking out the opponent, coaches and boxers should consider if additional training methods can be implemented within existing programmes to facilitate punch performance. One training method that may enhance the important kinetic and kinematic elements of punching, such as force (Turner et al., 2011), velocity (La Bounty, Campbell, Galvan, Cooke, & Antonio, 2011), power (Loturco et al., 2016), acceleration (McGill, Chaimberg, Frost, & Fenwick, 2010) and rate of force development (RFD) (Tack, 2013), is resistance training (RT).

Defined as 'a mode of training that requires skeletal muscles to produce force against an external resistance source' (Swinton, 2013; p.5), RT in various forms has displayed the ability to elicit significant physical and physiological improvements in elite athletes across a wide spectrum of sports (Bompa & Haff, 2009). However, as sports science has advanced, boxing has been plagued by archaic misconceptions, often refusing to accept the improvements observed in many sports as a result of RT (Price, 2006). This hesitancy stems from popular myths that are commonplace within the boxing community, such as RT increases body mass, produces muscular 'stiffness' and diminishes aerobic endurance capabilities (Bourne, Todd, & Todd, 2002; Ebben & Blackhard, 1997; Klatten, 2016; Zekas, 2016). Although boxing has a reputation for avoiding RT, amateur boxing at the elite level has recently started to appreciate the performance improvements associated with it (AIBA, 2015b).

Knowledge of how to increase punching performance through RT is still in its infancy (Turner et al., 2011). Despite the global appeal of the sport, the majority of the boxing literature related to RT (Dengel et al., 1987; Getke & Digtyarev, 1989; Solovey, 1983), was written over two decades ago (commonly within the former Soviet Union).

From the results of these papers, RT was found to augment various aspects of amateur boxing performance including punching force, power and velocity (Cordes, 1991; Dengel et al., 1987; Getke & Digtyarev, 1989; Solovey, 1983). However, the aforementioned studies did not adequately describe the research methods employed, casting doubt on the validity of the findings. Additionally, due to advancements in the understanding of RT and evolution of amateur boxing as a sport (such as rule changes, scoring criteria and protective equipment requirements) (Bianco et al., 2013), previous findings are likely obsolete. Contemporary research cognisant of scientific principles is required to assess the effects of RT upon punching performance, and to provide coaches and boxers with a clear understanding of how training interventions can improve performance. Indeed, little is actually known about the punch performance benefits possible following a structured, controlled RT intervention. Moreover, given the potential of biomechanical assessments for informing specific RT strategies geared to improving punching performance (Lenetsky et al., 2013), there is considerable scope for investigation in amateur boxing.

1.2. Statement of aims

The aims of this programme of research were to (i) assess the kinetic and kinematic qualities of fundamental punching techniques performed by competitive amateur boxers; (ii) quantify the role and effect of MV to maximal punching, (iii) explore the physical performance-related characteristics associated with maximal punching performance; and (iv) examine the influence of various RT methods (interventions) on punching performance.

1.3. Research Questions

A series of research questions were formulated in order to address the above aims.

i. **Which kinetic and kinematic measures are associated with maximal punching performance across conventional punch techniques?**

Previous research assessing biomechanical features of boxing has discovered important kinematic features during the execution of certain punches. Kinematic properties such as linear and angular velocity of the upper extremities, fist displacement and peak velocity, are important qualities in the delivery and execution of those punches (Bernabeu et al., 2016; Cabral, João, Amado, & Veloso, 2010; Cheraghi et al., 2014). Although this data is available, its validity is questionable as most studies assessing the kinematics of maximal punches have not utilised three-dimensional motion capture systems which are considered the 'gold standard' of kinematic analysis (Piorkowski et al., 2011). Additionally, prior analyses have reported contrasting findings with respect to elbow joint velocities (Cheraghi et al., 2014; Whiting et al.,1988) and pelvic and trunk angular velocities (Cabral et al., 2010), all being presented as the principal kinematic determinants of punching performance. It is therefore clear that the distinct kinematic features of each conventional boxing punch technique are still be fully elucidated, and as such, a comprehensive analysis using a three-dimensional motion capture system is justified to understand the kinematic components of maximal punching. Furthermore, Mack et al. (2010) discovered maximal straight and hook punching forces correlated with the sum of lower body forces (GRF) produced by male amateur boxers. Su et al. (2013) also established that, when in a boxing stance, GRF produced by the lead foot correlated with the velocity of the jab punch in elite male boxers. Though these findings demonstrate that GRF production is a key component of punching performance, little is known about the direction of force application during different punching techniques.

ii. How does movement variability affect maximal punching performance and is it influenced by boxing experience?

Within- and between-subject movement variability (MV) are important to performance outcomes owing to the individual characteristics of performers, whereby different athletes often execute the same movements with varying techniques whilst still achieving similar outcomes (Bartlett et al., 2007). Indeed, the execution of dynamic full-body movements across various sports has identified the role of MV to successful performance (Button, MacLeod, Sanders, & Coleman, 2003; Handford, 2006; Morriss, Bartlett & Fowler, 1997; Robins, Davids, Bartlett, & Wheat, 2008; Schmidt, 2012; Scott, Li, & Davids, 1997; Wagner et al., 2012). When punching a target (opponent), boxers must concurrently judge the distance to it, select the specific technique to utilise, and assess how forcefully to perform the punch whilst it is still within ‘punching range’ (Choi & Mark, 2004; Hristovski, Davids, Araújo, & Button, 2006). Particular characteristics of boxing likely add to maximal punch MV, such as the boxer’s arm segment dimensions (limb lengths), pre-fight strategy, fighting ‘style’, and perceived efficiency (perception of own performance capability - Davids et al., 2006). Lenetsky et al. (2017) identified small-to-moderate variability for punch impact kinetics, though the extent of MV, its influence on the upper-body kinematics and lower-body kinetics of maximal punching, and its extent according to boxing experience is unknown. Research has yet to elucidate whether different punch types exhibit more MV than others, and why this might occur.

iii. Are physical performance-related characteristics associated with maximal punching?

Research has established a strong association between strength and power qualities and punching ability among amateur boxers (Chaabene et al., 2015; Loturco et al., 2016; Obmiński, Borkowski, & Sikorski, 2011). However, the absence of dynamic maximal strength assessments means it is still unclear whether muscular strength is an important factor in punching performance. Furthermore, the interaction between punching performance and physical attributes such as speed and acceleration have not been reported, which is surprising considering the importance of both variables to boxing performance (Chang et al., 2011; Loturco et al., 2014). Previous research suggests that augmenting muscular strength and power through RT may have the potential to improve performance, and if other physical properties have an influence on a boxer's punching capabilities, the creation of boxing-specific strength and conditioning strategies could be enhanced.

iv. Can resistance training programmes enhance maximal punching performance?

Having established the biomechanical properties and their associations with physical performance-related qualities of punches, it follows that subsequent research seeks to determine the optimal training method of augmenting these variables via training (Bishop, 2008). As the majority of essential physical properties required in competitive sport can be enhanced through the completion of specific RT programmes, a detailed analysis of punching performance following a RT intervention, including lower-body kinetics and upper-body kinematics, would provide insight into the effects of RT upon the biomechanics of maximal punches.

Within the present body of literature, RT programmes have been reported to enhance biomechanical and physical performance-related characteristics of punching performance. The most prominent method used in prior studies to improve boxing performance, particularly punching force and velocity, was strength training (ST) (Dengel et al., 1987; Getke & Digtyarev, 1989; Solovey, 1983). More recently, other researchers have identified straight and hook punch impact force improvements of up to 27% following ST programmes (Čepulėnas et al., 2011; Hlavačka, 2014; Kim et al., 2018). Additionally, Mathews and Comfort (2008) endorsed the implementation of contrast training (CT) into boxer's training programmes, however no empirical research has examined its effects on the upper-kinematics and lower-body kinetics of maximal punching. As RT (in various forms) can improve muscular strength and power, which both contribute to punching force and velocity (Loturco et al., 2016), an assessment of the efficacy of such training methods upon maximal punch biomechanics is warranted.

1.4. Organisation of Chapters

The programme of research presented in this thesis details the key biomechanical characteristics of fundamental punching techniques observed in amateur boxing, and the role of physical performance-related traits that influence them among senior male amateur boxers. Chapter 2 presents a review of literature relating to the aims of the thesis, including appraisals of research on maximal punch biomechanics, the physical and physiological traits related to maximal punching, and a critical evaluation of the strength and weaknesses of the various resistance training methodologies and their relevance to combat sports performance. Subsequent chapters detail the quantification of the kinetics and kinematics (Chapter 3) and MV (Chapter 4) of maximal punches, followed by an appraisal of the physical performance-related qualities underpinning maximal punches, and assessment of the relationship between maximal punch biomechanics and strength, power, and speed variables (Chapter 5). The fourth empirical study (Chapter 6) quantifies the effects of different RT interventions upon maximal punch kinetics and kinematics and physical performance-related qualities associated with maximal punching. The final chapter (Chapter 7) addresses the research questions established in Chapter 1, synthesises the novel findings of the thesis, highlights certain limitations of the research, and identifies potential directions for future research.

Chapter 2

Review of Literature

2.1. Introduction

Despite the global popularity of boxing at amateur level, the biomechanical and physical performance-related factors that influence punching performance have yet to be established within the scientific literature. Indeed, whilst numerous papers have reported research on the physiology of amateur boxing competition, the principal biomechanical and physical performance-related traits that relate to maximal punching performance have not been adequately established. Furthermore, no research has examined the effects of different RT programmes on the biomechanics of maximal punches and the physical traits that influence them. This absence of knowledge across these areas of performance suggests that the optimal training strategies to enhance punching performance remain unknown. This chapter appraises the pertinent research on a) the kinetics and kinematics of various punch techniques, b) the movement variability (MV) of these biomechanical variables, c) the physical performance-related qualities related to boxing punches, and d) the potential for a RT programme to enhance maximal punching performance.

2.2. Boxing Synopsis

2.2.1. Historical Overview

The sport of boxing can be traced back five millennia with evidence of unarmed hand-to-hand combat taking place in Sumeria and Ancient Egypt (Pierce, Reinbold, Lyngard, Goldman, & Pastore, 2006; Smith, 2006). Evidence also appears to highlight that boxing was widespread across North Africa and Mediterranean countries between 4000 BC and 1500 BC (Fleisher, Andre, Loubet, & Odd, 1989). Introduced in the Olympic Games of 776 BC, the first form of sporting combat to be contested was a striking and grappling hybrid known as ‘pankration’. This primitive event permitted the simultaneous use of both boxing and wrestling techniques with few rules representative of modern-day boxing competition (Hickey, 1980).

Hand-to-hand combat evolved into prize-fighting in the 17th century and comprised working class pugilists competing under the patronage of the middle and upper classes (Hickey, 1980; Smith, 2006). Similar to pankration however, it remained a violent pastime largely void of rules until 1742 when striking a downed opponent became prohibited and contests were halted if a competitor was unable to reach a standing position after 30 seconds (Perkins et al., 2014). Such rules however did little to reduce the prevalence of serious injury (Smith, 2006), and prize-fighting remained somewhat primitive until 1867 when John Douglas introduced the 'Queensbury Rules for the Sport of Boxing' in an attempt to improve the safety of the sport (Barker, 1998). Major changes to competition included the mandated use of padded gloves during bouts as opposed to bareknuckle combat, attempts to match competitors according to body mass instead of 'open-weight' competition, the implementation of 3-minute 'rounds' separated by 1-minute recovery intervals in place of unlimited bout durations, the prohibition of wrestling and/or grappling and the termination of a contest if a boxer was unable to reach a standing position after 10 seconds as a result of a knockdown caused by an opponent's punch.

The introduction of the Queensbury rules to prize-fighting not only enhanced the safety of competitors in professional boxing, but also prompted the growth of an amateur version of the sport that had materialised in the preceding years (Perkins et al., 2014). From 1881, the professional and amateur variants of boxing deviated along different paths, with professional boxing contested for prize money and amateur boxing becoming a 'vehicle for physical and personal development and the pursuit of virtue' (Perkins et al., 2014; p.10). Since then, amateur boxing has evolved to the point whereby the governing body (AIBA) currently has 201 national federations affiliated to its programme (Chaabene et al., 2015). The popularity of amateur boxing as an

Olympic sport has also enhanced over time, as demonstrated by an increase from 18 boxers (all from America due to the last minute decision to include boxing in the games) competing at the 1904 Olympics (Grasso, 2013) to 286 male and female boxers representing 76 nations at 2016 Rio Olympic Games (AIBA, 2017c).

2.2.2. Characteristics of Competition

Similar to other combat sports, amateur boxing is categorised by a series of weight classes that are 'intended to promote fair competition by matching opponents of equal stature and body mass' (Langan-Evans, Close, & Morton, 2011; p.25). Since the introduction of identifiable weight categories, boxers will characteristically attempt to participate in the lightest weight classification possible in anticipation of gaining a competitive advantage over opposing fighters (Morton, Robertson, Sutton, & MacLaren, 2010). Across all elite amateur boxing competitions, there are currently 10 weight categories for senior and youth male boxers and nine for senior and youth female boxers (Table 2.1) (AIBA, 2017a; Perkins et al., 2014). All 10 male weight categories are included in the Olympic Games programme, however only three of the female weight classifications are currently contested, with the 2012 London Olympiad being the first to allow female boxers to compete for medals. Additionally, there are various contest formats utilised pending the experience of the competing boxers; within the Olympic Games and at 'elite' competition (aged 19-40 years), all boxers (male and female) contest 3 rounds of 3-minutes. Furthermore, 'youth' boxers (aged 17-18 years) can take part in 3 x 3-minute rounds (male only), 3 x 2-minute rounds (male and female) or 4 x 2-minute rounds (male only), dependent upon an agreement between opposing coaches (AIBA, 2015a; Chaabene et al., 2015). Recovery intervals between rounds are 1-minute for all categories, classes and genders.

Boxing, both amateur and professional, has always been scored by judges in a subjective manner. Although several attempts have been made to objectify the scoring process (e.g. application of a computer-based system in which judges awarded points for ‘forceful, clean punches upon the target area’; Smith, 2006), the current method involves five judges using a 10-point must-system (whereby the winner of the round receives ten points whilst the other competitor receives nine or less). A boxer is judged to be victorious based upon the number of quality blows landed to a target area, domination of a bout via technical and tactical superiority and competitiveness (AIBA, 2017a).

As a full-contact combat sport, the aim of amateur boxing is to succeed in delivering a clean and correct punch to the opponent without being punched in return (Guidetti et al., 2002). The desired outcome of a contest is victory by way of knocking the opponent out, defined as the deliberate production of a state of motor hypotonus coupled with a severe disturbance of consciousness (Critchley, 1957). Within bouts, competitors are permitted to use various punching techniques, which are required to strike the frontal or lateral sections of the opposing combatant’s head and torso (Chaabene at al., 2015; Loturco et al., 2016).

Table 2.1. Current elite male, female, youth boy and youth girl amateur boxing weight classifications (adapted from AIBA, 2017a).

		Male - elite		**Male - Olympic Games**		**Female - elite**		**Female - Olympic Games**		**Youth boy**		**Youth girl**	
#	Weight category	Over kg	To kg	Over kg	To kg	Over kg	To kg	Over kg	To kg	Over kg	To kg	Over kg	To kg
1	Light-fly	46	49	46	49	45	48	-	-	46	49	45	48
2	Fly	49	52	49	52	48	51	48	51	49	52	48	51
3	Bantam	52	56	52	56	51	54	-	-	52	56	51	54
4	Feather	-	-	-	-	54	57	-	-	-	-	54	57
5	Light	56	60	56	60	57	60	57	60	56	60	57	60
6	Light-welter	60	64	60	64	60	64	-	-	60	64	60	64
7	Welter	64	69	64	69	64	69	-	-	64	69	64	69
8	Middle	69	75	69	75	69	75	69	75	69	75	69	75
9	Light-heavy	75	81	75	81	75	81	-	-	75	81	75	81
10	Heavy	81	91	81	91	-	-	-	-	81	91	-	-
11	Super-heavy	91	+	91	+	-	-	-	-	91	+	-	-

Note: - indicates weight category is not utilised by AIBA; + indicates no weight limit is imposed by AIBA.

Successful performance in amateur boxing is often determined by technical and tactical superiority (Davis, Leithauser, & Beneke, 2014), however Smith (1998) and Lees (2002) argue that the ability to throw repeated punches of sufficient force throughout the duration of a contest is also paramount to success. Although these studies were completed during the era of computer-based scoring (1989-2013), it is plausible the views proposed by Smith (1998) and Lees (2002) remain relevant to present day competition as aggression and ‘competitiveness’ are rewarded positively by judges.

Due to the alteration from an impressionistic to a computer-based scoring method in 1989, a greater importance was placed upon the development of punching force in straight punches (Dyson, Smith, Fenn, & Martin, 2005). Because judges scoring bouts using the computer system could struggle to reward boxers for numerous punches thrown rapidly, boxers began to implement strategies that focussed upon landing one or two forceful blows likely to be acknowledged by scoring judges (Dyson et al., 2005). However, the reversal back to impressionistic scoring in 2013 has not diminished the requirement of forceful punches within bouts. Pertinent to professional boxing, current amateur competition requires combatants to attack perpetually throughout all three rounds of a bout, with this strategy appearing to be the optimal approach to achieving success (Davis et al., 2013; 2015; El Ashker, 2011; Pierce et al., 2006). Indeed, elite amateur boxers can execute up to 300 punches during a fight (Święcicki, Klukowski, & Hűbner-Woźniak, 2013), suggesting repeated punching is a key requirement of successful performance.

The diverse range of punching techniques that comprise the offensive arsenal available to both amateur and professional boxers permits the opportunity to land damaging strikes from various angles and locations. The labels bestowed to the traditional punch types observed within boxing somewhat detail the trajectory that the punches travel when executed. Traditionally, there are three different punching classifications that are commonly observed. These comprise straight, hook and uppercut punches and such actions have served the sport of boxing consummately since the introduction of the Queensbury rules in 1867 (Billingham, 2015). The various punching techniques observed within boxing are listed in Table 2.2.

2.3. Punch techniques within boxing

Punching is an exceptionally dynamic and complex motion that emerges through the transfer of momentum via the kinetic chain (Cheraghi et al., 2014; Koryac, 1991). An intricate action comprising movement of the legs, trunk and arm musculature, a punch results in the fist acting as a rigid weapon projected at high velocity to cause physical damage to an opponent (Piorkowski, 2009; Turner et al., 2011). Research by Buse (2006) confirmed the effectiveness of punching as a method of causing damage within combat sports, discovering that striking (such as punching and kicking) was the prominent method of obtaining victory following the outcome analysis of 642 competitive mixed martial arts (MMA) contests. Of 182 contests decided via stoppage, 28.3% were due to head strikes and almost 60% of total stoppages were the result of punches. Put into perspective, the amount of contests stopped as a result of strikes were greater than victories secured by judges decisions (27%), musculoskeletal stress (16.5%), miscellaneous trauma (12.9%), choke submission (4.1%) and disqualification (1.0%). These results highlight that striking with the fists (i.e. punching) is still one of the most effective and widely used skills for successful performance in combat sport (Piorkowski, 2009), even within a sport that permits grappling, submission holds and striking with both upper and lower extremities.

Though many punches are thrown, research (Davis et al., 2018; Slimani et al., 2017; Thomson & Lamb, 2016) has established that straight punches (jabs and rear hand crosses) to the head of an opponent are the principal techniques performed within contemporary amateur boxing contests, with winning boxers executing an average of 35.4 ± 8.7 (Round 1), 30.4 ± 9.7 (Round 2) and 29.8 ± 6.9 (Round 3) during the course of a competitive bout (El Ashker, 2011). The underlying rationale behind this observation lies in the fact that straight punches have a linear trajectory and traverse over the shortest possible distance to the target (Blower, 2007), in addition to a rapid delivery time (357 ± 178 ms) compared to hooks (477 ± 203 ms) (Piorkowski et al., 2011), and presumably, uppercuts (no previous literature has identified the delivery time(s) of this punch type). Furthermore, as straight punches can be executed effectively without a need to pre-stretch the hip, trunk and shoulder musculature, they do not require as much energy to execute and can reach the target at a faster rate compared to hook and uppercut techniques (El Ashker, 2011). This is likely to benefit boxers in terms of their strategic planning prior to bouts, especially as the single most successful boxing strategy has been suggested to be executing a high frequency of straight lead-hand punches to the head (Davis et al., 2013).

El Ashker's (2011) paper ascertained that hook punches were the second most popular punch technique performed to the head of an opponent in competitive bouts by winning boxers with average frequencies of 12.6 ± 6.4, 11.3 ± 5.3 and 9.2 ± 3.5 in rounds one, two and three, respectively. Meanwhile, uppercuts were performed far less frequently with values of 2.4 ± 1.1 (Round 1), 2.9 ± 1.8 (Round 2), and 1.6 ± 0.9 (Round 3) recorded. It can be reasoned that hook punches are the most effective strike thrown once combatant's are at 'medium range' (boxers do not have to step forward to deliver punches; Table 2.3) as straight punches are not as damaging to an opponent at this distance owing to the limited space from which to generate force (AIBA, 2015c). Uppercut punches (usually executed at close range whereby the two combatant's gloves touch or almost touch; Table 2.3) are the least frequently observed punch within contests, particularly when aimed at the head of an opponent (El Ashker, 2011). It is suggested that the scarcity of uppercuts in competitive contests results from the strike being the most difficult technique to master (Kapo et al., 2008), necessitating the shortest distance between a boxer and the target (Hristovski, Davids, Araújo, & Button, 2006) and the counter-attacking opportunities afforded to an opponent given the close proximity between boxers (Thomson & Lamb, 2016).

In order for a boxer to land a forceful blow within a contest, high levels of physical and physiological fitness are required alongside technical proficiency (Davis et al., 2013). Although the risk of being struck by an opponent is ever present, boxers must be committed to offensive techniques if punches are to be landed forcefully. The ability to land forceful, accurate punches at a high frequency is a vital strategy for amateur boxers as this is likely to influence the decision of scoring judges. In terms of forceful punching, while knock-outs in amateur boxing are far more infrequent than in the professional variant of the sport, knock-outs do still occur and it remains the most conclusive end to a boxing contest (Mack et al., 2010). Accordingly, boxers seeking a knock-out victory require considerable muscular strength and power. Possessing such physical traits in addition to correct punching mechanics/technique, considerably elevates the potential of scoring a knock-out blow (Chaabene et al., 2015; Kravitz, Greene, Burkett, & Wongsathikun, 2003; Loturco et al., 2016).

Straight punches are the most frequent punches performed within competitive bouts, most commonly when combatants are standing at long range (Table 2.3) (El Ashker, 2011). These punches are valuable techniques to perform due to the speed at which they can be delivered and the distance that can be maintained from an opponent, even when attacking. Furthermore, straight punches are arguably easier to perform and are less physically demanding than other varieties of punches due the lower degree of technicality and coordination required (El Ashker, 2011). There are two types of straight punches performed within amateur and professional boxing; the jab and rear-hand cross.

When executed correctly, hook punches follow a ‘sweeping’ trajectory whereby the arm is swung in a circular motion about the transverse axis to strike an opponent outside their line of vision (Whiting et al., 1988). Hook punches are most commonly performed when a boxer is at ‘medium’ range (punches can be landed by either combatant without the need to reduce the distance). Similarly to the rear-hand cross, both lead and rear hooks are powerful strikes due to the inherent degree of body rotation required to perform the punch. An additional factor responsible for the scale of force generated by hook punches is the proximity of the arm to the body. Throughout the punch, having the shoulder horizontal to the ground and the arm flexed to a 90^{o} angle at the elbow (for a traditional hook punch) allows for a highly efficient transfer of force from the ground to the fist (Turner, 2009a).

Table 2.2. Punch techniques in boxing (adapted from Thomson, Lamb, & Nicholas, 2013).

Punch classification	Punch technique	Definition
Straight	Jab	A straight punch from the lead hand that moves along the sagittal plane from anterior to posterior with the elbow fully extended at an angle of 180° and the fist pronated upon impact with the opponent/target.
	Rear-hand cross	A straight punch from the rear hand that moves along the sagittal plane from anterior to posterior with the elbow fully extended at an angle of 180° and the fist pronated upon impact with the opponent/target.
Hook	Lead hook	A punch from the lead hand that moves across the transverse plane in a sideward 'sweeping' motion with the shoulder abducted to an angle of approximately 90° to the torso and the fist in a neutral position relative to the forearm.
	Rear hook	A punch from the rear hand that moves across the transverse plane in a sideward 'sweeping' motion with the shoulder abducted to an angle of approximately 90° to the torso and the fist in a neutral position relative to the forearm.
Uppercut	Lead uppercut	A punch from the lead hand that moves along the sagittal plane and the longitudinal axis. Beginning with a downward projection and ending with an upward projection, the elbow is flexed at an angle of 90° and the fist in a supinated position.
	Rear uppercut	A punch from the rear hand that moves along the sagittal plane and longitudinal axis. Beginning with a downward projection and ending with an upward projection, the elbow is flexed at an angle of 90° and the fist in a supinated position.

If landed with force and delivered with technical competence, the hook is perhaps the most hazardous punch (in a physiological sense) because if the fist connects with an unguarded jaw, the cervical spine is twisted laterally resulting in an almost certain knock-out (Arus, 2013). Traditionally, there are two types of hook punches within a boxer's offensive arsenal; the lead hook and rear hook.

The uppercut punch is principally implemented when boxers are at close/short range and is perhaps the most under-utilised punch in boxing (El Ashker, 2011), with both lead and rear uppercuts observed at a lower frequency (5 and 8 respectively) among 92 regional and national level boxers across 46 contests than straight (jab - 64; cross - 39) and hook (lead - 49; rear - 23) punches (Thomson & Lamb, 2016). This observation was also noted among elite-level international boxers across 29 bouts whereby uppercut punches accounted for only 6.6% of total punches thrown in comparison to straight (52.86%) and hook (40.5%) techniques (Davis et al., 2015). As with hook punches, uppercuts are forceful strikes (1546 N - Viano et al., 2005) due to the proximity of the arm to the body (punching arm in a vertical position and the arm flexed at a 90^{o} angle at the elbow). The position of the punching arm in relation to the centre of mass (CoM) during uppercuts, particularly the rear uppercut, permits this technique to be executed with considerable force and velocity due to the muscular torque generated at the hip, trunk and shoulder (Cabral et al., 2010). There are two types of uppercut punches performed within boxing; the lead uppercut (hand nearest the opponent) and rear uppercut (hand furthest from the opponent). From an orthodox stance, the lead uppercut is executed with the left hand and the rear uppercut with the right hand (vice versa 'southpaw' boxers).

All of the punches detailed previously can also be performed to the torso of an opponent. Body punching is a highly effective strategy within boxing due to its ability to weaken an opponent, lower his/her guard to allow more openings for head punches and even bring about a stoppage/knock-out if landed to the correct part of the body (Arus, 2013; Haislet, 1968). Although body blows can be effective from long range using the jab and rear-hand cross, they are arguably more effective when delivered at close/short range (Murphy & Sheard, 2006). This is possibly due to the trajectory of hook and uppercut punches allowing a boxer to strike a specific area of the torso that straight punches cannot reach easily whilst an opponent is situated in the traditional boxing stance. This area, known as the ‘floating ribs’, is considered to be the optimal location to cause damage to an opponent’s torso. The ‘floating ribs’ comprise the eleventh and twelfth ribs on the ribcage and are named as such due to the fact they are not attached to the sternum or cartilage of other ribs (Coletta, 2009; Miles & Barrett, 1991).

Although body punches can be effective techniques and provide a significant target (front, left side and right side of the abdomen), they are far less frequent than punches to the head. This was stressed by Davis et al. (2013) who observed that across three rounds of elite-level competition, the total number of punches to the body (Round 1 – 7.2 ± 6.3, Round 2 – 6.5 ± 5.1, Round 3 – 7.0 ± 5.8) was five times lower than punches to the head (Round 1 – 39.4 ± 11.9, Round 2 – 33.9 ± 9.6, Round 3 – 35.2 ± 9.9). This statistic is notable given body punches were more accurate than head punches for all six punch types (jab, rear-hand cross, lead and rear hook, lead and rear uppercut) across bouts contested at the 2012 Olympic Games (Davis et al., 2015). Murphy and Sheard (2006) suggest that amateur boxing competitors have focussed solely upon head shots in competition as they are more likely to be seen by judges and, subsequently, scored by judges. Even though body punching was not a prominent characteristic of amateur boxing in years previous, the computer scoring system greatly reduced the incentive to pursue this tactic and therefore encouraged boxers and coaches alike to favour head punches in both training and competition (Davis et al., 2013; Murphy & Sheard, 2006). It was plausible that the subsequent introduction of the same 10-point-must scoring system as used in professional boxing would incite a greater quantity of body punches within bouts than previously observed in the amateur variation of the sport. However, the findings of contemporary research suggest body punching has decreased further since the introduction of the new scoring system (Davis et al., 2015; 2018). The authors propose that this may be related to judges still not rewarding body punches as favourably as head punches, and more interestingly, that boxers now place a greater emphasis on scoring a head shot ‘knock down’ or knock-out due to the removal of head guards (2013).

2.3.1. Key performance indicators of traditional punches

Although the study and analysis of biomechanics is an effective way of enhancing sports performance, particularly within martial arts (Mustapha, Mahmud, Zakaria, & Sulaiman, 2015), there is a notable absence of empirical evidence concerning boxing (amateur or professional). Since punching technique is an essential component of successful boxing performance (Davis et al., 2014), it is remarkable so little research exists relating to the biomechanics of boxing punches.

With regards to the kinetics of boxing punches, for example, uncertainty exists concerning which direction force is produced by the lower body during different techniques. Punching biomechanics share common traits with sporting activities such as javelin (Bouhlel, Chelly, Tabka, & Shephard, 2007; Whiting, Gregor, & Halushka, 1991), shot put (Obmiński et al., 2011; Terzis, Georgiadis, Vassiliadou, & Manta, 2003) and baseball pitching (Oliver & Keeley, 2010) in that there is notable distal-to-proximal sequencing with force being transferred from the ground via triple extension of the ankle, knee, and hip to the upper extremities.

Gulledge and Dapena (2008) reported that horizontal GRF was an important component of forceful rear hand punches among male martial artists, but failed to examine vertical forces. Moreover, Cesari and Bertucco (2008) discovered greater anterior centre of pressure (CoP) movements than posterior among experienced karatekas (karate practitioners) who punched a designated target. Although Cesari and Bertucco (2008) concentrated the findings on the participant's proficiency in maintaining dynamic stability, their study can be used to highlight the path of force produced during a punch (Lenetsky et al., 2013).

While the importance of the biomechanical characteristics cannot be understated, the act of punching is also heavily influenced by physical performance-related qualities that, in combination with kinetics and kinematics, contribute to the optimal execution of the various strikes. Despite boxing often being referred to as the 'sweet science', there are few research papers that have gathered evidence relating to the physical and physiological requirements of the sport (Arseneau, Mekary, & Léger, 2011; Del Vecchio, 2011). Contemporary papers such as those by Chaabene et al. (2015) and Loturco et al. (2016) have contributed greatly to knowledge in this area, but there remain facets of boxing physiology, particularly in relation to punching, have not been investigated adequately. For example, Turner et al.'s (2011) paper suggested that a boxer's ability to enhance the rigidity of their lead leg prior to the initiation of trunk rotation was a primary component required to maximise the impact force of the rear-hand cross.

Table 2.3. Classification of distance within boxing (adapted from AIBA, 2015c).

Distance between boxers	Classification
Long range	Competitors are at such a distance that punches cannot land without the closing of distance via displacement of the legs (Loturco et al., 2016). If a boxer wants to land an offensive strike to the head of torso of the opposing combatant, s/he must step forward with the lead leg to do so. The most frequent strikes performed at this range are straight punches (jabs and rear hand crosses).
Medium range	Punches can be landed by either combatant without the need to reduce the distance from the opponent. At this range, hook and uppercut punches (with varying degrees of elbow flexion and shoulder abduction) (Hristovski et al., 2006) and straight punches without full elbow extension are suggested to be the most frequent strikes performed.
Short/close range	Competitors are at such a distance that the combatant's gloves are touching or almost touching. At this range, due to the diminished distance between boxers, uppercuts and short hooks (very compact technique with a large degree of elbow flexion) are the most frequent strikes executed.

However, despite this noteworthy judgement, no subsequent studies have attempted to verify Turner et al.'s (2011) verdict. Therefore, ascertaining the physical performance-related traits associated with punching, and subsequently relating these traits to pre-determined kinetic and kinematic information, would appear to be a highly worthwhile pursuit that could be beneficial to boxers.

In addition to improving the many technical areas that comprise amateur boxing (e.g. footwork, evasiveness), it is unquestionable that enhancing a boxer's punching performance is also a desired outcome of training and contest preparation. Therefore, the synthesis of biomechanical and physical performance-related analysis is crucial to not only discovering the mechanisms and physical traits that influence punching, but also how performance can subsequently be optimised (i.e. sport-specific strength and conditioning regimen).

2.3.2. Jab

The jab is a punch thrown with the lead arm (arm nearest to the opposing combatant) in a linear motion towards the opposing boxer along the sagittal plane (Figure 2.1). It can be broken down into four phases; preparatory, initiation of motion, impact, and recovery phases. A jab will generally be thrown from the 'guard' position (preparatory phase) from which both the lead elbow and rear knee joints begin to extend, which in turn produces rotation at the trunk (initiation of motion phase). At the conclusion of the impact phase, the lead elbow is extended to an angle of 180° whilst the lead shoulder is internally rotated and the lead fist pronated with the palm facing the ground (Sandoval-Gonzalez et al., 2009) after following a linear pathway towards the target. In addition, the rear knee is typically extended, the lead knee moderately flexed, the lead hip medially rotated and the trunk anteriorly rotated to an angle that facilitates the greatest degree of protraction at the lead shoulder (dependent upon the initial ‘guard’ position of the individual). Following impact with the target, the lead knee extends and the rear knee flexes whilst the lead elbow flexes, the lead shoulder retracts and the trunk rotates. This is classified as the recovery phase and concludes with the boxer attaining the initial ‘guard’ position, permitting the ability to perform further offensive or defensive manoeuvres.

The jab to the head of an opponent is arguably the most versatile punch in a boxer’s repertoire and is the most frequently executed within competitive bouts (Davis et al., 2013; 2015; 2017; 2018; El Ashker, 2011; Kapo et al., 2008; Thomson & Lamb, 2016). In addition to being a punch of great speed, the jab can also be used to assess the distance necessary for delivering a further punch of greater force (such as a rear-hand cross). The versatility of the jab punch allows it to be thrown effectively moving towards an opponent, moving away from an opponent or from a stationary position, making it an essential skill (Arus, 2013; Markovic, Suzovic, Kasum, & Jaric, 2016).

It is suggested by Davis et al. (2013; 2015; 2018) that a successful strategy within competitive bouts is for a boxer to perform a high frequency of straight lead-hand punches (i.e. jabs). In fact, the authors asserted that in order for boxers to land a high frequency of successful clean punches (including rear-hand punches and lead hooks), the single most effective strategy is to throw the jab to the head of an opponent with great regularity. This is further corroborated by El Ashker (2011) who verified that winners of competitive contests performed a considerably greater quantity of jabs compared to losers, especially within the third round (24.7 ± 8.6 versus 19.8 ± 17.5). The results of these studies imply that a strategy comprising a high volume of jabs may be a successful tactic for boxers to employ. Nonetheless, Davis et al. (2015)

identified that the accuracy of the jab was of greater importance than the frequency with which it was performed. This is supported by James, Robertson, Haff, Beckman, and Kelly (2016b) which, although MMA-based, suggests that it is the accuracy of offensive techniques as opposed to the volume performed that is most critical to successful performance in combat sports.

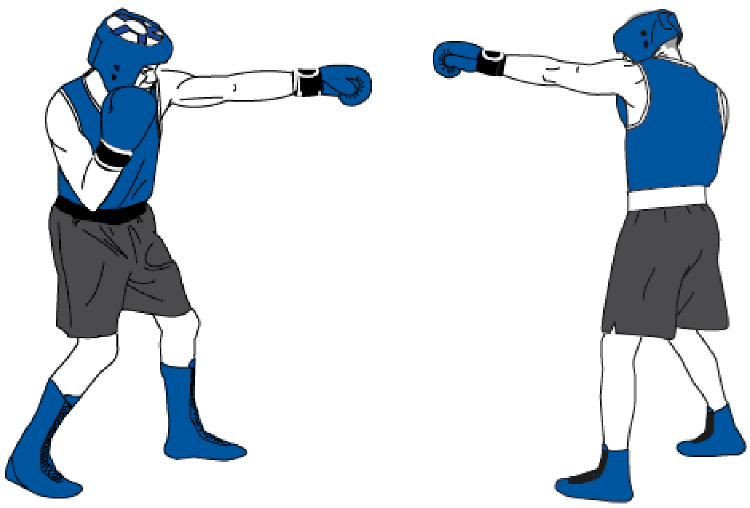

Figure 2.1. Jab from an orthodox stance (AIBA, 2015c; p. 42).

2.3.3. Rear-hand cross

The rear-hand cross (also known as the reverse straight or rear-hand straight) is another form of straight punch (Figure 2.2), thrown with the arm furthest from the opposing combatant (referred to as the ‘rear’ arm). From the guard position, the initiation of motion phase begins with ankle, knee and hip extension of the rear leg, which in turn produces rotation of the trunk, in addition to rear shoulder protraction and elbow extension. Upon impact with the desired target the ankle and knee of the rear leg are at near maximal plantar flexion and flexion respectively whilst the rear hip (relative to the position of the puncher's body to the target) is medially rotated and at near-maximal extension. In terms of the upper body, the rear elbow is fully extended, the rear shoulder internally rotated and fully protracted, the rear fist pronated and rear side of trunk (relative to the target) anteriorly rotated towards. The recovery phase of the rear-hand cross encompasses rear knee flexion, flexion and lateral rotation of the rear hip, rear arm flexion, rear shoulder retraction and external rotation, moderate rear fist supination and rotation of the trunk in the posterior direction. The phase is finalised once the boxer arrives back to the initial guard position, ready to throw another punch when required.

The rear-hand cross is arguably the foremost 'power' punch observed not only in boxing competition, but all combat sports (Turner et al., 2011). This is likely due to the degree of rear leg drive and trunk rotation alongside the distance over which the punch travels to its target (Cheraghi et al., 2014). The rear-hand cross can be a damaging strike as forceful punches to the anterior segment of the mandible can induce elements of physiological trauma such as nausea, equilibrium instability and unconciousness (Salah, 2012). This results from the cervical spine being forced into considerable hyperextension in conjunction with subsequent retro-flexion of the head (Unterharnscheidt & Unterharnscheidt, 2003). With regards to frequency, Kapo et al. (2008) documented that the rear-hand cross accounted for 15.5% of total punches recorded following an examination of punch selection and punch volume among 80 'first-rank' male amateur boxers from Bosnia and Herzegovina competing in 4 x 2-minute rounds of competitive boxing. Although this study assessed boxers over this bout duration as opposed to 3 x 3-minute rounds as used in present male competition, the authors arrived at a similar conclusion to that of El Ashker (2011) and Davis et al.

(2018), stating that the rear-hand cross executed with force is imperative to successful performance in amateur boxing.

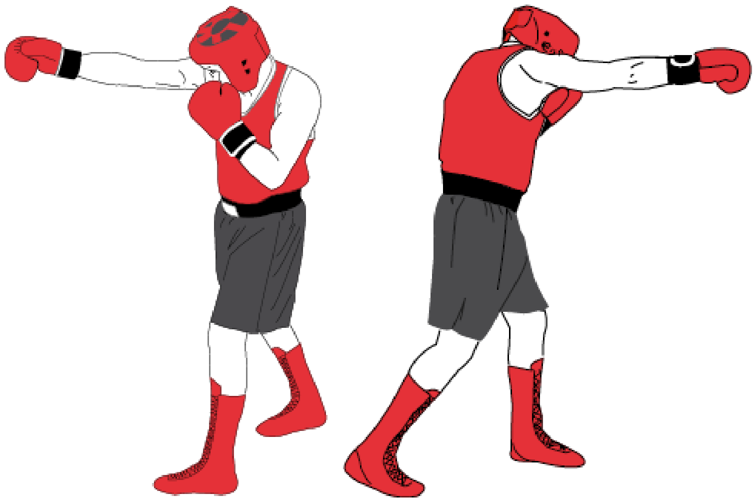

Figure 2.2. Rear-hand cross from an orthodox stance (AIBA, 2015c; p. 43).

2.3.4. Lead hook

The lead hook performed at medium range is a forceful punch completed with a sweeping motion of the lead arm in combination with considerable rotation of the trunk. From the guard position, the lead hook is usually performed with a slight counter movement prior to the punch from which a combination of plantar flexion and medial rotation of the lead ankle joint and medial rotation of the lead hip occur whilst the lead leg remains in a slightly flexed position throughout. The medial rotation of the ankle and hip triggers rotation of the trunk along the anteroposterior axis which subsequently creates a pre-stretch at the shoulder joint of the lead arm. Simultaneously, there is abduction and slight protraction of the lead shoulder with the elbow joint flexed to an approximate 90° angle and the fist placed in a neutral position (neither supinated or pronated) relative to the forearm. At the point of impact, the elbow of the lead arm is flexed to an angle of 90° (forearm relative to the upper arm) and the lead shoulder perpendicular to the ground (also to a 90° angle). Additionally, the lead shoulder will have travelled from abduction to adduction. With regard to the lower limbs, the lead ankle is plantar flexed and exhibits a large degree of medial rotation whilst the lead knee will be slightly flexed and the lead hip (left side for an orthodox boxer; right side for a southpaw boxer) also demonstrates a large degree of medial rotation (Figure 2.3). The rear hip knee remains in a somewhat neutral position relative to the torso and the rear knee slightly flexed throughout the technique. The recovery phase of the lead hook encompasses lateral rotation of the lead hip and ankle, slight flexion of the lead knee and rotation of the trunk whilst the upper limbs return to the initial guard position ready to execute further strikes. The lead hook is the second most frequently executed punch within competition according to Kapo et al. (2008) (23.2% of total punches) and Thomson and Lamb (2016) (26.7% of total punches).

The lead hook can be used as both a damaging punch (i.e. knock-out blow) and as a ‘set-up’ punch (to create openings for other strikes). As the lead hook travels rapidly about the longitudinal axis with an extensive proportion of rotatory elements comprising the technique, the fist is propelled with considerable force to the lateral section of an opponent’s cranium (Sandoval-Gonzalez et al., 2009). This results in considerable trauma being placed on the head and neck of a boxer via translational and rotational accelerations. Previous research has documented average shear neck forces of 855 ± 537 N (Viano et al., 2005) and 994 ± 318 N (Walilko et al., 2005), jaw loads of 876 ± 288 N (Walilko et al., 2005), translational accelerations of 71.2 ± 32.2 G (Viano et al., 2005), 58 ± 13 G (Walilko et al., 2005) and 43.6 ± 15.6 G (Smith, Bishop, & Wells, 1988) in addition to rotational accelerations of 9306 ± 4485 rad/s^2 (Viano et al., 2005), 6343 ± 1789 rad/s^2 (Walilko et al., 2005) and 675.9 ± 230.6 rad/s^2 (Smith et al., 1988) as a result of the lead hook punch.

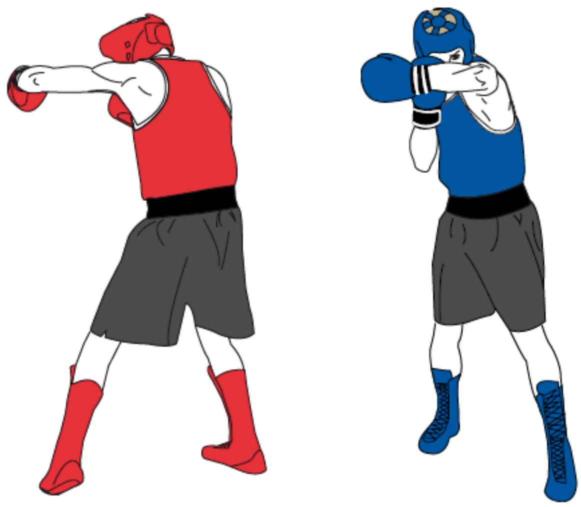

Figure 2.3. Lead hook from an orthodox stance (AIBA, 2015c; p. 47).

2.3.5. Rear hook

The rear hook is a strike of great force that travels across the transverse plane of motion to strike an opponent. Similar to the lead hand equivalent, the rear hook is usually performed with a slight counter movement to generate a greater degree of force upon the strike's impact. From this counter movement position, the initiation of the motion phase begins with a combination of plantar flexion and medial rotation of the rear ankle joint and medial rotation and extension of the rear hip whilst the lead leg remains in slightly flexed position throughout. This is superseded by rear trunk rotation (relative to the target) in the anterior direction, subsequently creating a pre-stretch at the shoulder joint of the rear arm (comparably with the lead hook). Simultaneously, there is abduction and slight protraction of the rear shoulder with the elbow joint flexed to an approximate 90° angle and the fist placed in a neutral position relative to the forearm. At the point of impact, the elbow of the rear arm is flexed to an angle of 90° (forearm relative to the upper arm), the rear shoulder perpendicular to the ground (also to a 90° angle) and the trunk slightly flexed and rotated. In terms of the lower limbs, the rear hook is almost identical to the rear-hand cross in that the ankle of the rear leg is plantar flexed, the rear knee almost at are maximal extension whilst the rear hip (relative to the position of the puncher's body to the target) is medially rotated and at maximal extension (Figure 2.4). The recovery phase of the rear hook involves rear knee flexion, rear hip flexion and lateral rotation, rear shoulder retraction and moderate rear fist supination and rotation of the trunk in the posterior direction. The phase is finalised once the boxer arrives back to the initial guard position, ready to throw another punch.

Following the assessment of elite-level male amateur boxers, Davis et al. (2015) concluded that the optimal strategy for successful performance is the implementation of an effective rear hook technique, as this strike can significantly influence the outcome of competition. This was based on observing that the rear hook landed at higher percentages for winners than losers of bouts in both the second (P = 0.038) and third rounds (P = 0.016). According to Haislet (1968), the rear hook is the most forceful punch in all of boxing, a view substantiated by Turner (2009a) as the proximity of the arm to the body allows for a highly efficient transfer of force from the ground to the fist. A forceful rear hook to the lateral segment of the jaw can cause intense physiological and neurological disturbances due to violent rotation of the jaw upon impact, including a broken/fractured mandible or unconsciousness (Arus, 2013).

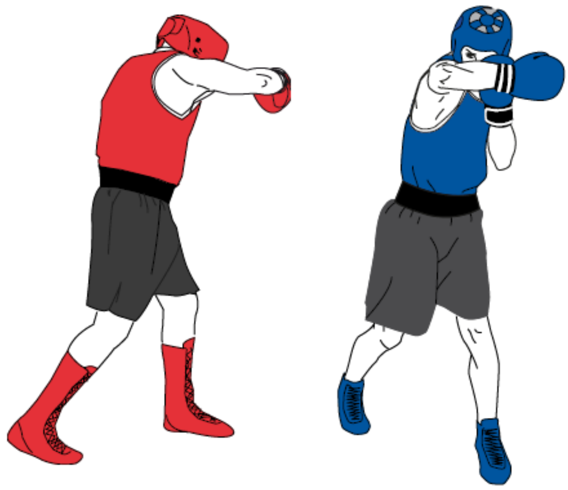

Figure 2.4. Rear hook from an orthodox stance (AIBA, 2015c; p. 48).

2.3.6. Lead uppercut

The lead uppercut (Figure 2.5) is primarily aimed to land underneath the opposing combatant's chin, causing the head to jolt upwards and the neck to hyper-extend (Arus, 2013). It can be used as both a damaging punch by itself or as a 'set-up' punch to force openings in an opponent's defence. The lead uppercut punch is often initiated in a 'dipped' position (knees flexed, upper body crouched) and follows an inferior-to-superior (low-to-high) ascending trajectory along the sagittal plane and about the mediolateral axis (Thomson et al., 2013). From the 'guard' position (preparatory phase), the lead elbow and shoulder flex, the lead knee extends, the trunk rotates, and the lead fist begins to supinate (initiation of motion phase). At the conclusion of the impact phase, the lead elbow flexes to an angle of approximately 90°, the lead shoulder flexes and protracts whilst the lead fist supinates. Commonly, the lower limb activity for the lead uppercut is near identical to that of the lead hook, albeit with a lesser degree of hip, knee and ankle medial rotation. Following impact with the target, the lead knee extends, the lead arm flexes, the lead shoulder extends and retracts, the lead fist pronates and trunk rotates. This is classified as the recovery phase and concludes with boxer attaining the initial ‘guard’ position, permitting the ability to perform further offensive or defensive manoeuvres.

As a result of the lead uppercut’s trajectory, it can be difficult for opposition boxers to observe the path of the blow (Arus, 2013), and owing to this, the possibility of causing damage is considerable with the opponent having limited time to react. Despite the potential effectiveness of this technique, Kapo et al. (2008) established that the lead uppercut to the head of an opponent was the punch thrown with the lowest frequency in competitive bouts (0.4% of total head punches). Thomson and Lamb (2016) also found the lead uppercut was the least frequently observed strike in competitive bouts, accounting for only 2.7% of total punches thrown. Uppercut punches in general (both lead and rear variations) are also the least observed punches among elite boxers, with only ~7.2 out of ~167.1 punches (4.3%) being an uppercut across 50 World Championship contests (Davis et al., 2018). Various explanations for this have been suggested within the literature. For example, Kapo et al. (2008) suggest how the uppercut technique is a highly-specialised skill, possibly the most difficult punch to master in boxing (Kapo et al., 2008), whilst Thomson and Lamb (2016) propose that because uppercuts are commonly performed at close/short range, both boxers would be in range to strike one another and subsequently provide opportunities for the opponent to land forceful strikes. Meanwhile, Davis et al. (2018) postulate that since uppercut punches are executed at ‘close’ range, it can be difficult for judges to observe whether a punch has landed cleanly. Subsequently, uppercut punches may not be rewarded as highly as straight punches whereby a clean strike is more noticeable. The papers of Davis et al. (2018), Kapo et al. (2008) and Thomson and

Lamb (2016) demonstrate how although elite-level boxers execute more uppercut punches than national and regional level competitors, the lead uppercut is still the least observed punch in competition compared to straight, hook and rear uppercut punches, regardless of ability level.

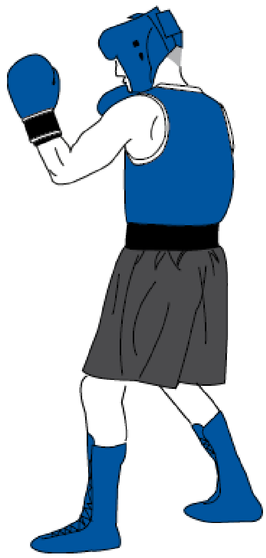

Figure 2.5. Lead uppercut from an orthodox stance (AIBA, 2015c; p. 52).

2.3.7. Rear uppercut

Comparably to the lead version of the punch, the rear uppercut is thrown at close/short range and follows an upward trajectory along the sagittal plane and around the mediolateral axis. From the ‘guard’ position, the initiation of motion phase leading up to impact involves the rear elbow flexing to a 90° angle, the rear fist supinating, whilst the rear shoulder flexes. The trunk and lower body motion that comprises the rear uppercut is similar to that of the rear-hand cross and rear hook, including triple-extension of the rear ankle, knee and hip, rotation of the trunk and rear shoulder protraction.

The rear uppercut can be thrown with greater force than the lead uppercut resulting from the distance over which the rear uppercut travels to reach its target, whereby a larger degree of trunk rotation and rear leg drive is present compared to the lead variation (Figure 2.6). The rear uppercut is a more commonly observed punch than its lead counterpart in amateur boxing contests, comprising 1.6% - Kapo et al., 2008) and 4.3% (Thomson & Lamb, 2016) of total punches respectively among national boxers, arguably because it can be executed with greater force and can also be an effective counter-punch (Haislet, 1968).

Figure 2.6. Rear uppercut from an orthodox stance (AIBA, 2015c; p. 53).

2.3.8. Influence of competition upon punch selection

At all levels of competition, boxers must possess the ability to throw forceful punches with both the lead and rear fists with technical efficiency. This view is highlighted through data collected by Davis et al. (2013) which revealed how punching combinations initiated with a lead-hand punch and finalised with a rear-hand cross or rear hook punch accounted for 62% of the variance in contest winners, with successful boxers executing a larger frequency of such punch combinations than losing boxers. This paper, in addition to El Ashker (2011), also suggested that the most successful strategy within competitive bouts is for a boxer to perform a high frequency of straight lead-hand punches (jabs). Although it may appear from the literature that straight punches, comprising the jab and rear-hand cross are the most important punches to master in boxing, a contemporary study by Davis et al. (2015) disputes this notion. This research created an activity profile based upon video footage of elite male amateur boxers competing at the semi-final (19 bouts) and final (10 bouts) stages of the 2012 London Olympic Games. The findings suggested that possessing a technically proficient rear hook influences the outcome of competitive bouts more so than performing a high frequency of lead-hand strikes. However, the authors only analysed the total frequencies of punches, failing to provide a temporal analysis. It would appear plausible to suggest that a considerable quantity of rear hook punches were landed by winning boxers due to their ability to implement successful ‘set up’ strategies, such as the use an effective jab for example.

Following the recent rule and scoring system changes, Davis et al. (2018) attempted to observe if the tactics and activity profiles of competitive boxers had changed as a result. It was discovered that since the changes, successful boxers favour effective straight punching techniques (jabs and rear-hand crosses) as opposed to the rear hook technique. The authors propose that due to the removal of head guards, boxers are more defensively-minded which has resulted in a greater distance between them, more defensive manoeuvres being performed (~2.5 defensive actions before the rule change; ~3.6 after the rule change – Davis et al., 2015; Davis et al., 2018), and consequently an increase in 'long' distance punches such as jabs and rear-hand crosses.

Davis et al. (2015) deemed punching accuracy to be of greater importance than punch frequency/volume as a declining ratio of punches thrown to punches landed across the three rounds was observed, including a lower ratio in victorious boxers compared to the losers. However, Davis et al. (2018) state that as a result of the new scoring system, punching accuracy is perhaps not as important as when the previous scoring system was utilised, and so, boxers should ensure punches strike the opponent with notable force, even if they do not land cleanly. This view insinuates than simply throwing a greater volume of punches than the opponent could be viewed more favourably by judges. However, it seems reasonable to propose clean punches should be rewarded more favourably than punches that strike non target areas (such as the gloves, arms and shoulders).

In addition to selecting the most effective punch technique to use at a given moment during a contest, the punch selection of a boxer is influenced by numerous factors such as strategy, skill level and characteristics of the opponent and boxer themselves (e.g. anthropometry, technical skill, tactical approach and physiology). As a result, boxers must decide the degree of force they wish to impart to each punch they execute within a contest. Pierce et al. (2006) examined the punching forces associated with lead and rear-hand punches of boxer's mid-contest against 'live' opponents rather than forces recorded from a static target within a laboratory setting. The participants were professional boxers ranging from junior-lightweight (otherwise known as super-featherweight) to heavyweight (n = 12) across six professional contests. Punching forces were recorded using a measurement device placed underneath the padded knuckle section of each boxing glove (‘Bestshot System’) which provided force data through a transmitter and receiver. The results revealed maximal lead-hand punch forces of 1873-2558 N for junior-lightweight boxers across four rounds and 2415-3416 N for the heavyweight combatants over six rounds. Maximal rear-hand punches were 2153-3554 N for the junior-lightweight and 2869-3554 N for the heavyweight boxers, respectively. No other raw data relating to the maximal punch forces for the lead or rear hand was provided for the boxers competing in the additional weight categories within the study. Unfortunately, the authors did not choose to document the forces for each specific punch type and instead selected to merge straight, hook and uppercut punches into basic ‘lead’ and ‘rear’ hand categories. Nonetheless, notwithstanding the small sample size, the results highlighted that maximal force values and did not correlate with body mass, suggesting various aspects of boxing competition including contest strategy, punch force ability and an opponent’s presence can influence the degree of force that a boxer will assign to their punches.

Notwithstanding the data presented, the current body of research on punch selections, volumes and profiles within amateur boxing was completed during the use of computer-based scoring rather than the 10-point-must system used in present-day competition. Therefore, the results of these studies may not accurately represent the nature of current competition as judges are encouraged to reward aggressive strategies in addition to clean punches landed (otherwise termed as bout ‘domination’ and ‘competitiveness’) (AIBA, 2015a; p. 12). It is reasonable to suggest the introduction of the 10-point-must scoring system will lead to an elevated quantity of punches thrown per round and across the duration of contests at both novice and elite levels. Consequently, a need for more contemporary research in this area is required to achieve a general understanding of an amateur boxer’s technical, tactical and strategic methods under the new scoring system.

2.4. Biomechanics of punching

2.4.1. Kinematics of boxing performance

2.4.1.1. Fist velocity

Walilko et al. (2005) sought to quantify the kinematic elements of jab punches completed by seven Olympic boxers across various weight categories (48 kg to 109 kg). Subjects were required to strike a hybrid dummy with a frangible face-form that contained accelerometers and pressure sensors to measure acceleration and force upon impact. Kinematic data was recorded using high-speed video cameras enabling the calculation of peak hand velocity. In addition, accelerometers were placed in the boxer’s hand during trials to monitor impact data. The study’s findings revealed a non-significant relationship between jab peak fist velocity (8.16 ± 1.38 m/s) and weight category (P = 0.779), indicating how this variable was not linearly associated with boxer’s body mass. Unfortunately, the authors analysed both jab and rear-hand cross punches and chose to group the hand velocity results together. Furthermore, no differences between punch type and their subsequent velocities were analysed. Piorkowski et al. (2011) also analysed fist velocities during the jab, documenting a peak velocity of 7.22 ± 0.72 m/s for the fist upon impact with the target. These results differ slightly from those within Kimm and Thiel’s (2005) study which noted jab velocities of 8.1 ± 1.4 m/s and 6.6 ± 1.6 m/s by experienced male and female boxers, respectively, through the use of a high-speed video camera and accelerometers fixed to the wrist of each boxing glove.

In terms of the rear-hand cross technique, Atha et al. (1985) assessed punch velocity using high-speed cameras in addition to an instrumented target with integrated force transducers and accelerometers. The peak fist velocity of 8.9 m/s upon impact with the target was similar to the results of later research (Viano et al., 2005) for the rear-hand cross to the jaw (8.2 ± 1.5 m/s) and the forehead (9.2 ± 1.7 m/s), respectively. Walilko et al.'s (2005) findings of 9.14 ± 2.06 m/s for rear-hand cross peak hand velocities also resemble those of Atha et al. (1985), Viano et al. (2005), Cheraghi et al. (2014) (7.8 ± 1.5 m/s) and Piorkowski et al. (2011) (8.22 ± 1.08 m/s). However, Walilko et al. (2005) amalgamated the hand velocity measurements of jab and rear-hand cross punches, making direct comparisons difficult.

The fist velocity for the rear-hand cross within Whiting et al. (1988 - 5.9 ± 1.1 m/s), Bingul et al. (2017 - southpaw stance = 4.18 ± 1.2 m/s, orthodox stance = 5.34 ± 1.38 m/s), and Tong-Iam, Rachanavy and Lawsirirat (2017 - 6.36 ± 0.45 m/s) are lower than those found in the studies of Atha et al. (1985), Cheraghi et al. (2014), Viano et al. (2005), and Walilko et al. (2005), possibly owing to the data collection methods and technical ability of the subjects across the various studies. Based upon the findings of previous research (Slimani et al., 2017; Smith et al., 2000; Thomson & Lamb, 2016), elite and/or more experienced boxers possess greater technical skill and mastery than less experienced competitors. More hours spent mastering technique(s) alongside a boxer's specific anthropometry and requisite physical attributes (e.g. strength/power production) likely account for the greater values noted for experienced boxers compared to their novice and intermediate counterparts. Consequently, the testing of a world-ranked professional boxer (Atha et al., 1985) and eighteen Olympic-level amateur boxers (Viano et al., 2005; Walilko et al., 2005) may explain the superior punch velocities reported in these studies compared to those noted for the ‘proficient’ and ‘elite’ boxers in Whiting et al.’s (1988) and Bingul et al.’s (2017) papers, and Muay Thai kickboxers with professional boxing records in Tong-Iam et al. (2017), respectively.

The lead hook punch, analysed by Viano et al. (2005), was found to have an average peak velocity of 11.0 ± 3.4 m/s, which is comparable to that of Piorkowski et al. (2011) who reported 10.61 ± 1.07 m/s for the same strike. The velocity of the rear hook technique has been investigated by Whiting et al. (1988) and Piorkowski (2009) through both 2D and 3D kinematic analysis, respectively. Whiting et al. (1988) obtained linear and angular velocities for various locations comprising the right upper extremity, including the shoulder (2.8 m/s), elbow (5.8 m/s), wrist (9.8 m/s) and fist (12.5 m/s). The authors reported a mean punch contact velocity of 8 ± 2.4 m/s, considerably lower than Piorkowski et al.’s (2011) rear hook contact velocities of 11.01 ± 2.21 m/s in experienced boxers. Although it could be argued that the subjects within Piorkowski et al.’s (2011) study were perhaps more technically skilled than those in Whiting et al. (1988), the method of analysis is also an aspect that must be considered as 3D motion capture systems (as used in Piorkowski et al., 2011) are more accurate at analysing complex full-body movements performed at great speeds, such as punching, than 2D systems (as used in Whiting et al., 1988) (Shan & Zhang, 2011), with sampling rates being the key determining factor (Baca, 2014).

Uppercut punches have not been researched as extensively as straight and hook punches. The principal studies that have investigated this punch are those of Viano et al. (2005) and Cabral et al. (2010). Viano et al. (2005) examined the velocity of the fist during rear uppercut punches to the jaw of a hybrid dummy with a frangible face-form. Akin to the study by Walilko et al. (2005), the hybrid dummy contained accelerometers and pressure sensors to measure velocity (in addition to force and head acceleration) upon impact and an average impact velocity of 6.7 ± 1.5 m/s was recorded for the rear uppercut punch. That punch velocities of the lead uppercut have not been quantified previously reinforces the distinct lack of kinematic data available for such a fundamental punch, and as such, means its quantification is worthwhile to inform coaches and boxers to the velocity of this punch so that performance changes can be subsequently monitored.

2.4.1.2. Punch delivery time

Previous research has documented delivery times of 100 ms (Atha et al., 1985) and 132 ± 21 ms (Whiting et al., 1988) for the rear-hand cross among professional and 'proficient' boxers. These times are lower than those of Cheraghi et al. (2014) (310 ± 0.06 ms) and Piorkowski et al. (2011) (353 ± 183 ms) for the same punch. This is due to the varying punch 'initiation' points between studies, with Atha et al. (1985) and Whiting et al. (1988) considering the extension of the elbow to be the initiation of a rear-hand cross punch, while the onset of ankle motion (Cheraghi et al., 2014) and rear leg counter movement (i.e. vertical GRF) (Piorkowski et al., 2011) defined punch initiation in the other studies.

For hook punches, Whiting et al. (1988) noted a mean delivery time of 143 ± 24 ms for the rear hook, with Piorkowski et al. (2011) reporting a higher mean time of 508 ± 243 ms, respectively. Once more, these notable differences between studies likely relate to the contrasting event markers (instant of shoulder abduction versus vertical

GRF data) and contrasting kinematic measurement analyses (3D - Piorkowski et al., 2011; 2D - Whiting et al., 1988). Piorkowski et al. (2011) is also the only study of note to have documented lead hook delivery times (446 ± 150 ms). Moreover, no previous research has investigated the delivery times of uppercut punches (lead or rear hand), further emphasising the dearth of research afforded to this punch type. Quantifying the delivery times of different punches would provide information to coaches and boxers that could help inform contest preparation strategies (e.g. punches with lowest delivery time(s) afford an opponent less time to defend/evade).

2.4.1.3. Acceleration

A detailed body of literature is available relating to the acceleration of the head after a punch impact, however, very little data exists on the acceleration of a punch itself. Walilko et al. (2005) discovered that maximal rear-hand cross punches generated a mean linear acceleration of 62 ± 11 *g* and mean angular acceleration of 6030 ± 2103 rad/s^2, values that were significantly correlated with a boxer's body mass. Bingul et al. (2017) reported that rear-hand cross punches from an orthodox stance (424.67 ± 104.94 m/s^2) exhibited greater accelerations than the same punch from a southpaw stance (328.09 ± 65.83 m/s^2) in elite boxers. Meanwhile, Piorkowski (2009) ascertained average vector accelerations for the jab (6.86 ± 2.26 m/s^2), rear-hand cross (8.36 ± 3.34 m/s^2) lead hook (5.39 ± 5.02 m/s^2) and rear hook (6.04 ± 4.47 m/s^2) punches. Interestingly, both the elbow and wrist generated the highest velocities and displayed elevated acceleration peaks prior to impact with the target. The authors hypothesised that the differences in acceleration for the different punch types assessed were affected by the relationship between joint range of motion, counter movement and length of acceleration pathway for each technique. The hypothesis of Piorkowski (2009) supports Bolander et al.'s (2009) finding that peak acceleration is reached close to the point of maximal elbow extension in straight punches, explaining why boxers and martial artists are encouraged by coaches to punch 'through' a target in order to impart a greater fist acceleration upon impact, which may also enhance the impact force of the strike (Loturco et al., 2014).

2.4.1.4. Joint angles

The joint angles present at the elbow during the rear-hand cross were assessed in the study of Joch, Fritsche, and Krause (1981) among elite, national-level and intermediate-level boxers (n = 24, 23, and 23 respectively), and it was found that the typical elbow angles displayed by all the boxers, regardless of ability level, were 50-70° at the onset and 110-130° at contact with the target. Whiting et al. (1988) noted how following a linear trajectory towards the target in the sagittal plane, minimum (52 ± 9°), maximum (102 ± 16°) and contact (102 ± 17°) angles of the elbow joint were documented for the rear-hand cross.

Cheraghi et al. (2014) determined that rear-hand cross punches travel in the sagittal plane along the anteroposterior axis. This study along with Bingul et al. (2017) are the only ones of note that have attempted to verify the angle of the shoulder joint during a boxing punch, specifically the rear-hand cross. Bingul et al. (2017) reported impact shoulder angles of 84.3 ± 8.9° for rear-hand cross punches thrown from an orthodox stance, and 83.6 ± 8° from a southpaw stance. Meanwhile, Cheraghi et al.'s (2014) findings revealed an 'onset angle' (joint angle at the initiation of motion from the guard position) of 20 ± 4° and an 'impact angle' (joint angle upon impact with the target) of 86 ± 5°. Additionally, the participants recorded a maximum shoulder joint angle of 90 ± 5°. The angle of the elbow joint was also analysed with mean maximum and impact elbow angles (143 ± 12° and 137 ± 12°, respectively) recorded during maximal rear-hand crosses. These results differ from the maximal elbow angle of 110 ± 130° reported by Joch et al. (1981) and the impact elbow angle of 102 ± 17° noted by Whiting et al. (1988), probably owing to the participant's technical execution of the technique and the accuracy of the measurement equipment used.

Additional kinematic assessments unique to the papers of Cheraghi et al. (2014) and Bingul et al. (2017) are the angles of the hip, knee and ankle joints during the rear-hand cross. Cheraghi et al. (2014) reported the hip joint had minimum (195 ± 6°), maximum (211 ± 4°), onset (203 ± 3°) and impact (196 ± 7°) sagittal plane angles during maximal rear-hand cross punches, while mean angles of 163.89 ± 8.51° (orthodox stance) and 156.67 ± 6.71° (southpaw stance) were reported by Bingul et al. (2017). The anterior superior iliac spine, also known as the ASIS (anterior extremity of the iliac crest and a prominent bony landmark of the pelvis) advanced in the direction of the punching target by a notable margin of 28 cm from the initial position. This was explained to be the result of the participants shifting their body mass forwards in the direction of the target, via motion at the hip and pelvis, to generate greater impact forces.

Sagittal plane knee joint angles ranged from 155 ± 7° (minimum) and 167 ± 9° (maximum) with angles of 164 ± 4° and 165 ± 12° noted at the onset and impact of the punch, respectively (Cheraghi et al., 2014). Meanwhile, impact knee angles of 162.9 ± 7.9° (orthodox) and 162.1 ± 8.9° (southpaw) have also been reported (Bingul et al., 2017). The authors suggested that the extension of the knee and subsequent leg drive caused the body mass of the participants to travel anteriorly towards the target. This has been shown by previous authors (Lenetsky, Nates, Brughelli, & Harris, 2015; Walilko et al., 2005) to augment the forces generated by proximal-to-distal sequencing in addition to enhancing the effective mass (i.e. inertial contribution, Lenetsky et al., 2015) and end-point velocity of a strike. Meanwhile, the ankle joint also plays a principal role in the performance of the rear-hand cross as it contributes significantly to the proximal-to-distal (kinetic chain) sequence. An onset angle (dorsiflexion) of 73 ± 27° and an impact angle (plantarflexion) of 98 ± 13° were documented, underlining the range of motion that the ankle joint covers during the rear-hand cross punch. In addition, the authors observed a considerable weight transfer from the rear foot to the lead foot which resulted from forceful extension of the rear leg (although the authors did not state how this was measured). Nevertheless, the anterior weight transfer from the rear to lead leg and consequent forward motion corroborate the notion that leg drive, via triple extension of the hip, knee and ankle, is perhaps the single most crucial contributor to punching performance (Lenetsky et al., 2013; Turner et al., 2011).

In terms of the joint angles during the rear hook technique, Whiting et al. (1988) reported minimum, maximum and target contact elbow flexion angles of 97 ± 11°, 116 ± 11° and 105 ± 15°, respectively. Whiting et al. (1988) in addition to Piorkowski (2009) also identified the motion and trajectory of the shoulder joint during rear (and lead) hook punches, however, neither of these studies assessed the angles present at this joint. Subsequently, the joint angle ranges at the shoulder during hook punches are still unknown. Although the angles of the hip, knee and ankle joints have also not been investigated, it is likely that these will be similar to those observed for the rear-hand cross due to the similarities in lower-body positioning during both strikes (Figures 2.2 and 2.4). Therefore, due to the lack of scientific evidence, the results of Cheraghi et al.'s (2014) paper may be a useful guide in terms of hip, knee and ankle joint angles during the rear hook.

Unfortunately, no research has investigated the joint angles present during the jab, lead hook, lead uppercut or rear uppercut techniques. The lack of knowledge appears surprising considering the offensive advantages (jab) and damage capabilities (lead hook, lead and rear uppercut) of these punch types to boxing performance (Arus, 2013; Haislet, 1968; Viano et al., 2005; Walilko et al., 2005).

2.4.1.5. Joint velocities

Lockwood and Tant (1997) examined the linear velocities of the wrist, elbow and shoulder during maximal jabs performed by amateur and professional boxers. Despite the lack of raw values presented, the results highlighted significant differences ($P < 0.05$) in wrist and elbow velocities during jab punches between professional boxers and their amateur counterparts, with professionals recording superior punch velocities. The researchers concluded that this was the consequence of professional boxers having greater technical competency resulting from greater neuromuscular adaptations to training (Cordes, 1991; Lockwood & Tant, 1997).

Whiting et al. (1988) utilised 2D motion analysis to assess the kinematics of joints that comprise the punching arm during the rear-hand cross (shoulder, elbow, wrist and fist) by participants with 'proficiency' in boxing. Despite peculiarly referring to rear-hand cross punches as 'jabs' within the paper, linear joint velocities for the shoulder (2.4 m/s), wrist (6.3 m/s) and fist (6.6 m/s) in addition to maximum linear and angular velocities (6.0 m/s and 1261 ± 320 deg/s) and angular velocity at contact (1117

± 405 deg/s) for the elbow were documented. Piorkowski et al.'s (2011) research was the first to utilise a 3D motion capture system (ProReflex MCU240 system, Qualisys Inc., Gothenburg, Sweden) to analyse various punch types, including the jab. Following the completion of maximal jab punches against a life-size strike dummy, the authors documented a maximum elbow extension angular velocity of 852 ± 254 deg/s and a maximum shoulder abduction angular velocity of -400.3 ± 100.7 deg/s.

Cheraghi et al.'s (2014) research analysed the kinematics of rear-hand cross punches performed by elite male boxers. In addition to the elbow angular velocities mentioned previously, maximal linear velocities of the shoulder (3.1 m/s), elbow (6.7 m/s), wrist (7.4 m/s) and fist (7.8 m/s) from the 'ready' position to the point of impact were detailed. The joint velocity results of Cheraghi et al. (2014) are similar to those of Nakano, Lino, Imura, and Kojima, (2014) who utilised a 3D motion capture system (MX-F20 system, Vicon, Oxford, UK) to document upper-extremity joint velocities associated with the rear-hand cross. The upper arm (5.0 ± 0.5 m/s), forearm (7.5 ± 0.9 m/s) and fist/glove (8.7 ± 0.9 m/s) velocities are similar despite Nakano et al. (2014) using a target that provided a degree of movement/mobility when struck. The un-fixed target had a similar mass to that of a human head (4.24 ± 0.32 kg) which it can be argued offered the boxers a target better resembling what would be encountered in competitive bouts (in terms of punching to the head of an opponent). Furthermore, the use of a target with a degree of mobility upon impact likely encouraged the boxers to punch with maximal intensity without fearing injury, an issue that can surface when using immobile targets (Atha et al., 1985).

Piorkowski et al. (2011) also highlighted the role of the elbow and shoulder joints during the rear-hand cross, with maximum elbow extension and shoulder abduction angular velocities of 695.5 ± 222 deg/s and -199.3 ± 240.6 deg/s observed, respectively. The angular velocity of 695.5 ± 222 deg/s noted in Piorkowski et al. (2011) for the shoulder joint is considerably less than the 1261 ± 320 deg/s (Whiting et al., 1988) and 2363 ± 536 deg/s (Cheraghi et al., 2014) documented for the same variable in other papers; it is likely the different motion capture systems used (3D versus 2D) and sample rates explain this discrepancy (Baca, 2014; Shan & Zhang, 2011).

Cabral et al. (2005) attempted to quantify the velocity of the trunk, hip and upper arm body segments during maximal rear uppercut punches, discovering a notable proximal-to-distal sequence with peaks in the pelvic (765.2 ± 29.5 deg/s), trunk (866.7 ± 42.5 deg/s) and punching arm (1404.6 ± 102.2 deg/s) angular velocities (unfortunately, the authors did not present proximal-to-distal sequencing timings). The proximal-to-distal sequencing pattern was initiated in the lower limbs and proceeded distally through the pelvis, trunk, and arm before arriving at the fist. Presently, there is no research available relating to joint velocities observed during lead hook, rear hook, and lead uppercut punches, meaning that their quantification is warranted to provide key biomechanical information that can be used to monitor boxer's performance changes/progressions following training interventions and/or practices.

2.4.2. Kinetics of boxing performance

2.4.2.1. Ground reaction force (GRF) and impulse

Ground reaction force (GRF) is a kinetic variable that plays an essential role in punching performance. The only study of note that has assessed this area in relation to the jab punch is that of Yan-ju et al. (2013). Within this paper, boxers performed jab punches at a fixed target whilst standing with their lead and rear legs on separate force plates. Results indicated that the force produced by the lead leg was a significant contributor ($P < 0.01$) to maximal jab punching performance. Conclusions from studies support the view that leg drive is a critical component of forceful punching, though unfortunately, no GRF or impulse (the product force, multiplied by the time that a force acts, McGinnis, 2013) values were reported. More specifically, it appears that lead leg drive is essential to jab performance (Yan-ju et al., 2013) whilst rear leg drive is critical to rear-hand cross performance (Cheraghi et al., 2014; Turner et al., 2011). However, it is difficult to interpret from research which direction force was produced to the greatest capacity (i.e. vertically or horizontally). Although Lenetsky et al. (2013) states leg drive during punching requires GRF to be developed in both vertical and horizontal directions, understanding how lower body force is generated during the jab punch could provide insight as to how to implement specific RT exercises that will enhance force production in the optimal direction. Indeed, whilst its relevance has been alluded to (Lenetsky et al, 2013), no scientific studies have examined the directional (anteroposterior, mediolateral, vertical) application of GRF and/or impulse during specific punch types.

2.4.2.2. Punch impact force and impulse

Though the effectiveness of a punch depends upon the accuracy and velocity of the strike (Piorkowski et al., 2011), previous research highlights punching force is also a necessity within competition. In a contest, the boxer who is able to consistently throw a high quantity of punches with accumulative force is typically deemed the victor (Pierce et al., 2006; Smith, 2006). Despite being stated prior to the introduction of the new scoring system, the view of Dyson et al. (2007) and Smith and Draper (2006) that peak punching force is a critical component of successful amateur boxing performance still holds true. Consequently, the ability to assess and monitor the punching force of amateur boxers seems logical to augment the chances of success within competition.

Several studies have assessed the force of the jab with wide-ranging results, likely due to the varying devices utilised to record punch force. After assessing the jab punch force of elite (n = 7), intermediate (n = 8) and novice (n = 8) amateur boxers using a specialised boxing dynamometer, Smith et al. (2000) concluded that expert boxers were able to produce greater punching forces than the lesser-experienced/skilled combatants. This is highlighted in the jab forces of 2847 ± 225 N, 2283 ± 126 N and 1604 ± 97 N for expert, intermediate and novice boxers respectively. These results are similar to those of Lenetsky et al. (2017) who reported how ‘trained’ boxers exhibited larger jab punch forces (2547 ± 776 N) than ‘untrained’ performers (1411 ± 365 N) in addition to Dyson et al. (2005) which observed that competitive male amateur boxers produced average forces of 2722 ± 75 N with the jab.

A further study by Smith (2006) tested a selection of punch techniques performed by English international-level amateur boxers at both senior (n = 130) and junior (n = 26) levels and showed that senior boxers produced maximal forces of 1722 ± 700 N for the jab thrown to the head whilst the results of the junior boxers were not presented. The jab forces of the senior boxers are lower than those noted in Smith et al. (2000), suggested by the author to be the result of the significantly greater number of participants in the later study, though it appears more likely that different measurement methods between studies account for this difference. The results of Smith (2006) are larger than the 1103 ± 431 N maximal jab forces for male boxers discovered by Buśko et al. (2016) which utilised a modified dynamometric punch bag with embedded accelerometers, and ~1323 N of Tong-Iam et al. (2017) which used a

5 kg ‘punching ball’. However, it is difficult to establish whether the variances in jab punching forces can be attributed to the biomechanical and physical performance-related differences between the boxers or the diverse range of measurement devices used to record punching forces (or indeed, a combination of such factors). Loturco et al. (2016) also assessed the maximal jab punches of international male amateur boxers and used a wall-mounted force platform as the measurement tool. Boxers were asked to perform jabs from both standardised and self-selected positions in relation to the force platform. Punch forces of 1152 ± 246 N from the standardised position and 1212 ± 269 N from the self-selected position indicate how important the aspect of positioning is within boxing and how it can affect impact force.

In terms of the rear-hand cross, Joch et al. (1981) reported punch forces of 3453 N, 3023 N and 2932 N for boxers of elite, national, and intermediate-level, respectively. These results are slightly lower than those found in the paper of Smith et al. (2000) who recorded maximum forces of 5771 N and 4390 N for elite and intermediate boxers, respectively, and Lenetsky et al. (2017) who reported maximum forces of 4695 ± 673 N (‘trained’ boxers) and 2395 ± 966 N (‘untrained’ performers). Additionally, a peak force of 1966-2851 N was also documented for novice boxers from Smith et al.’s (2000) research. Viano et al.’s (2005) study recorded punch forces of 2349 ± 962 N for the rear-hand cross to the jaw and 3419 ± 1381 N to the head of a hybrid dummy. It is unclear why the punch to the head produced greater force values than the equivalent strike to the head, although a possible explanation could lie in that the boxers were more focussed on accuracy than force when striking the jaw which comprises a smaller surface area than the forehead. Smith (2006) found that a rear-hand cross punch to the head produced an average force of 2643 ± 1273 N among senior elite amateur boxers, although unlike Viano et al. (2005), it was not stated whether the participants were required to punch a particular area of the striking target (i.e. jaw or forehead). This suggests that peak impact forces are affected when boxers are required to punch with a degree of accuracy (i.e. jaw vs forehead), suggesting Viano et al.'s (2005) results may arguably possess greater external validity than those of other studies that did not necessitate accurate punching.

Chadli et al. (2014) and Nakano et al. (2014) reported results of considerable differences, despite both studies testing collegiate boxers (n = 11 and n = 9, respectively). The differences between the 1162 N (Chadli et al., 2014) and 2146 ± 473 N (Nakano et al., 2014) can likely be explained through both studies using unique measurement devices to document rear-hand cross forces. Whereas Nakano et al. (2014) implemented an un-fixed punch target the size and weight of a human head, the authors of Chadli et al. (2014) attached accelerometers to a punching target in addition to the inside of each boxer's gloves. Due to the uniqueness of each study's measurement equipment, it is difficult to accurately compare the results to one another or other papers that utilised various devices. Such measurement equipment contrasts may also explain the punch force differences between previous research and the contemporary papers of Buśko et al. (2016) and Loturco et al. (2016). Indeed, Buśko et al. (2016) recording punch forces of 1592.5 ± 507.1 N, and Loturco et al. (2016) 1331 ± 234 N for the rear-hand cross from a standardised position and 1368 ± 266 N from a self-selected positions, respectively.

Walilko et al.'s (2005) research examined Olympic-level boxers (n = 7) from varying weight-categories with, unsurprisingly, the super-heavyweight boxers (n = 2) producing the greatest rear-hand cross punch forces (4345 ± 280 N) across all participants. The authors determined that the effective mass of the combatants assisted in the promoting of force generation. An unexpected result of this study however was that the flyweight boxers (n = 3) demonstrated greater punching forces than the light-welterweight and middleweight combatants (3336 ± 559 N compared to 2910 ± 835 N and 2625 ± 543 N, respectively). The authors did not allude to why this punch force variance may have occurred. It can be surmised that either the flyweight boxers were able to strike the target with great force (by being able to utilise their effective mass to a greater degree), the small sample size influenced the mean data values, or the punch force measurement device was not accurate.

For the lead hook, Lenetsky et al. (2017) documented peak forces of 4058 ± 109 N in 'trained' boxers which is greater than those reported by Viano et al. (2005) among Olympic boxers (3107 ± 1404 N and 4405 ± 2318 N from the head of a hybrid dummy and the boxer's fists, respectively), and those of Smith (2006) who noted peak punch forces of 2412 ± 813 N across elite-level senior amateur boxers for the lead hook. Although both subject groups are classified as being 'elite', the results from both studies reinforce the notion that boxers at the highest level (the Olympic Games for amateurs) can execute complex punching techniques more efficiently and dynamically than boxers of a lesser standard (Kimm & Thiel, 2015; Lenetsky et al., 2015). However, the differing force measuring equipment between studies might have also influenced the values obtained.

Lenetsky et al. (2017) determined that the rear hook was the most forceful punch across all straight and hook punches, recording peak impact forces of 4749 ± 107 N and 2427 ± 940 N among 'trained' and 'untrained' performers, respectively. In contrast, Smith (2006) identified the rear hook as being the third most forceful punch in amateur boxing (2,588 ± 1,040 N), behind the rear-hand cross to the body (2,646 ± 1,083 N) and rear-hand cross to the head (2,643 ± 1,273 N). However, it can be suggested that the fighting 'style' of a boxer can influence how forceful they execute particular punch techniques. For example, a tall boxer will commonly perform jab and rear-hand cross punches with greater force than hook and uppercut punches, thought to be the result of the greater acceleration path that can be generated. Kimm and Thiel (2015) confirmed that a boxer's stature correlated with straight punch velocity, determining that the further the hand travels (due to the length of the upper extremity), the more time there is available to accelerate the fist. However, Smith (2006) did not provide the stature values for the boxers analysed, therefore it is unclear whether this element factored in the rear hook punch force scores documented.

Viano et al., (2005) discovered peak forces of 1546 ± 857 N for the rear uppercut technique in boxers. Though due to this being the only study of note within the literature that has attempted to collect kinetic data related to the rear uppercut, comparisons with other findings cannot be made. No research has assessed the kinetic characteristics of the lead uppercut punch. Arguably, this is due to the majority of previous punch force measurement devices being created and/or designed to assess straight and hook punches rather than uppercuts (e.g. force plates/platforms, dynamometers, regular punch bags). Furthermore, the limited use of lead uppercut punches in competitive bouts, as discovered by Kapo et al. (2008), may also explain why researchers have not assessed the biomechanics of the lead uppercut in great detail.

These findings serve to highlight the forces associated with maximal punches among boxers. Understanding the impact forces of different punches could provide coaches and boxers with an insight as to which punch(es) is most likely to cause damage to an opponent, and subsequently, influence contest preparation depending upon pre-fight strategies/tactics. Furthermore, integrating punch force and kinetic and kinematic assessments will enable an all-inclusive analysis of maximal punches that could assist in the development of strength and conditioning programmes with the aim of augmenting the biomechanical characteristics of the techniques.

2.4.3. The interaction of kinetics and kinematics on maximal punching

Understanding the kinematic and kinetic components that comprise maximal punching is essential to understanding how the body produces force and motion. Of particular importance is identifying how kinematic and kinetic elements of punching, particularly GRF and pre-impact hand/fist velocity, influence each other to produce a strike of maximal intensity. Cheraghi et al. (2014) established the importance of leg drive, particularly the rear leg, to the velocity of the gloved fist upon impact with an intended target. Leg drive from the rear leg to lead leg (produced via plantar-flexion of the ankle joint and extension of the knee joint) was of considerable importance to upper-extremity velocity as this ‘drive’ instigates considerable motion in the sagittal plane, culminating in the forces produced by the legs being transferred to the fist via a kinetic chain. This subsequently enhanced proximal-to-distal sequencing during the punch, fostering a greater degree of momentum and velocity (Bartlett, 2007). Filimonov, Koptsev, Husyanov, and Nazarov (1985) and Verkhoshansky (1991) also highlighted that the legs and trunk contribute 76% and 78% respectively of the force (referred to as ‘energy’) generated during a punch performed by experienced boxers. This force was the result of ankle, knee and hip joint triple extension at the rear leg, deemed to be the principal influence with the force being transmitted to the fist upon impact with the target.

The research of Mack et al. (2010) examined pre-impact hand velocities and GRF of rear-hand cross and rear hook punches completed by 42 male international-level amateur boxers. The hybrid dummy utilised to record punching impacts also contained 3 accelerometers, 3 angular rate sensors, a high-speed camera, and TrackEye Motion Analysis (TEMA - Photo-Sonics Inc.). These measurement devices documented the pre-impact hand velocities for the 2 punch types. Significant (P < 0.05) correlations were discovered between punch force and pre-impact hand velocity for rear-hand cross (r = 0.391) and rear hook (r = 0.380) punches. At the conclusion of the study, the authors suggested that pre-impact hand velocity of both 'dominant-side' cross and hook punches provided a greater indication of punch force than the sum of lower body forces (measured using a FAB system - Biosyn Systems). However, the inference of Mack et al. (2010) is disputed by Cabral et al. (2010) and Cheraghi et al. (2014) who suggest the proximal-to-distal sequencing motion observed at the pelvis, trunk and arm (specifically the shoulder joint) is influential to pre-impact hand velocities of boxers. Unfortunately, no angular velocity timings were presented in these studies to reinforce such conclusions. Therefore, based upon previous recommendations (Fortin, Lamontagne, & Gadouas, 1995; Harris-Hayes, Sahrmann, & Van Dillen, 2009), the most valid, reliable and comprehensive method of assessing the biomechanics of punching would be the combination of leg GRF measurements taken from a force plate combined with kinematic measurements from a 3D motion capture system (Lenetsky et al., 2013).

2.4.4. Proximal-to-distal sequencing

Within the assessment and analysis of biomechanics in relation to sport and sporting techniques, there are many aspects of movement that can be examined with the concurrent analysis of kinetics and kinematics facilitating a comprehensive assessment of the descriptions of motion and the forces producing it. Within boxing for example, observing and assessing a phenomenon known as ‘proximal-to-distal sequencing’ (present throughout all punching techniques) facilitates the merging of kinetic and kinematic analysis.

Proximal-to-distal sequencing (also known as the kinetic or kinematic chain) is a universally accepted biomechanical mechanism whereby coordinated segmental motion between the upper-body, lower-body and trunk, such as punching, occurs at high-velocity (Baker & Farrow, 2015). The kinetic/kinematic chain incurs the preservation of angular momentum during whole-body movement which in turn allows for the transfer of force from the ground upwards to the upper-limbs (Cheraghi et al., 2014). During motion initiated by forces generated via the kinetic/kinematic chain, movement is transferred sequentially from the heavy centre points of the body such as the trunk (proximal) to the lighter, outermost points of the body such as the foot or the fist (distal) via successive joint accelerations and decelerations. In relation to its quantification, kinematic characteristics can be obtained through 3D motion capture analysis recording the technical aspects of punching while the kinetics producing the sequential punching motion can be analysed simultaneously via ground-embedded force plates.

The concept of proximal-to-distal sequencing, whereby the end-point speed of a distal segment is dependent upon the motion initiated by a larger proximal segment of the body, is considered to be an adaptation of Bunn’s (1972) ‘summation of speed’ principle. This principle suggests in order to optimise the end-point speed of a distal body segment at the conclusion of a linked movement chain, each succeeding distal body segment within the chain should commence motion at the moment of peak speed reached by the previous proximal body segment. This in turn allows each subsequent body segment to produce greater speeds than the previous segment along the proximal-to-distal pathway (Hirashima, Kadota, Sakurai, Kudo, & Ohtsuki, 2002).

Where boxing is considered, the relationship between proximal-to-distal sequencing and maximal punching has only been investigated within the study by Cabral et al. (2010). It was established that a proximal-to-distal sequence was noticeable within the uppercut punch technique with the initial motion instigated by the lower limbs and subsequently travelling distally through the body to cause rotation of the trunk via the kinetic chain. This chain then concluded with a stretch-reflex contraction of the shoulder joint which the authors believed to be the result of a temporal dissociation of the active muscles prior to impact with the punch target. Furthermore, during the acceleration phase of the punch, the trunk rotated around the longitudinal, medio-lateral and antero-posterior axis contributing considerably to the angular velocities of the pelvis and trunk in addition to the generation of large hand/fist speeds. Additionally, the rotation of the punching arm may also be considered a critical element of punching based upon the often overlooked principle of the proximal-to-distal sequence known as 'long-axis rotation' (Marshall & Elliott, 2000). In relation to Cabral et al.'s (2010) study, the angular velocities of the punching arm ($1404.58 \pm 102.23^{o}.s^{-1}$) reveal that longitudinal-axis rotation, upper arm internal rotation in particular, may also play a key role in the uppercut punch.

2.4.5. Kinetic and kinematic differences between punch types

Within the present body of literature, it is noticeable there are clear kinetic and kinematic differences between not only the punching techniques utilised, but also the hand that executes the punch (i.e. lead versus rear hand). Whiting et al. (1988)

highlighted the lead hook generated a significantly higher ($P < 0.01$) end-point velocity than the rear-hand cross (8.0 ± 2.4 m/s and 5.9 ± 1.1 m/s, respectively), hypothesising that the difference was the result of the punch's trajectory. The rear-hand cross travels linearly to the intended target whereas the lead hook 'sweeps' around the guard of the opponent, providing a greater range of motion and subsequent acceleration pathway.

Viano et al.'s (2005) study determined that the lead hook to the temple demonstrated the greatest velocity of all the punch types assessed (11.0 ± 3.4 m/s), followed by the rear-hand cross to the jaw (9.2 ± 1.7 m/s), rear-hand cross to the forehead (8.2 ± 1.5 m/s) and the rear uppercut to the jaw (6.7 ± 1.5 m/s). Moreover, the authors did ascertain that lead hook punches to the temple were the punch type with the greatest chance of causing concussions within competitive bouts (13.8% ± 14.3% risk of concussion) due to the location of impact which produced superior head acceleration impacts (71.2 ± 32.2 *g*) compared to the other punch types (rear-hand cross to jaw - 48.8 ± 20.9 *g*; rear-hand cross to forehead - 47.8 ± 20.1 *g*; rear uppercut to jaw - 24.1 ± 12.5 *g*).

Piorkowski et al. (2011) illustrated lead and rear hook punches (10.61 ± 1.07 m/s and 11.01 ± 2.21 m/s, respectively) generated significantly greater velocities upon impact with the intended target than jab and rear-hand cross punches (7.22 ± 0.72 m/s and 8.22 ± 1.08 m/s, respectively). Similarly to Whiting et al. (1988) and Viano et al. (2005), it may be hypothesised that the longer acceleration pathway allows hook punches to generate more acceleration than other punch types utilised within boxing. Indeed, the authors suggested that because the range of motion at the elbow joint is far less than that of the shoulder, the longer acceleration pathway of hook punches may allow a boxer to generate superior end-point fist velocities than with straight punch techniques. However, the authors also discovered that hook punches, whilst generating superior contact velocities, required a greater delivery time than straight punches. This can be explained through hook punches having to travel along a sweeping pathway across the transverse plane whereas straight punches travel linearly to their target via the sagittal plane. This technical difference between punch types reveals how different techniques can be utilised in varying ways by a competitive boxer dependent upon the opponent and/or competitive situation.

Kimm and Theil (2015) quantified the relationship between experience, reach (arm length) and jab and rear-hand cross punch velocities among experienced amateur boxers. Analysis demonstrated a moderate relationship between maximal jab velocities and boxing experience (r = 0.56), perhaps highlighting the assertion that boxing experience plays a principal role in the ability to deliver punches with technical expertise (Lenetsky et al., 2015; Smith et al., 2000). In addition, in the male boxers, jab punches achieved greater peak speeds than rear-hand cross punches. Similar results were also observed among the female boxers. The conclusions of this study concur with those of Cesari and Bertucco (2008), which although based within the sport of karate, found that experienced karatekas (categorised as 'expert punchers') were able to generate greater punch velocities than their less experienced counterparts ('amateurs'). Cesari and Bertucco (2008) theorised this was the result of the more experienced karatekas demonstrating superior stability during punches, subsequently decreasing the degree of backward centre of pressure (CoP) displacement which may limit force production capabilities. Unfortunately, the lack of an upper-body kinematic assessment within this study makes it is difficult to quantify if the greater punch velocities observed in the expert karate practitioners were primarily influenced by the upper or lower extremities.

The punch delivery times of Kimm and Thiel’s (2015) paper contradict those discovered by Piorkowski et al. (2011) which ascertained the action-to-contact time of jab punches (587 ± 186 ms) were inferior to those noted for the rear-hand cross (553 ± 211 ms) and lead hook punches (570 ± 168 ms) in experienced boxers. This finding contradicts boxing coaching practice whereby the jab is considered the ‘fastest’ punch (i.e. lowest delivery time) in a boxer’s arsenal (Hickey, 2006). It is likely the opposing outcomes observed between the two studies is because Piorkowski et al. (2011) required subjects to maximally punch a specialised target whereas the participants within Kimm and Thiel’s (2015) study had no target to aim for (punches were performed ‘in air’). Arguably, the study of Piorkowski et al. (2011) obtained findings of greater practical relevance as the presence of an actual punching target will have allowed subjects to throw punches with greater intensity than in Kimm and Thiel’s (2015) study, and subsequently, more accurately replicate maximal punch intensities observed in competition.

With regards to the differences between punches performed with the lead hand versus the rear hand, Buśko et al. (2016) discovered how the force of a straight rear-hand punch was greater than the force of a straight lead-hand punch among both male and female boxers. This conclusion is consistent with the studies that have assessed the punch forces associated with both lead and rear-hand punching techniques (Dyson et al., 2005; 2007; Smith et al., 2000; Smith, 2006). It is suggested that rear hand punches produce superior forces than the techniques performed with the lead hand as a result of the longer trajectory pathway, greater trunk rotation and the influence of rear leg drive observed across all rear-hand punch techniques (Hickey, 1980; Smith et al., 2000; Smith, 2006).

2.4.6. Movement variability

Though the majority of biomechanical appraisals of technique convey the salient features of motion, an emerging, yet important, focus concerns MV. MV is an aspect that considers the influences of intra- (task-to-task variation) and inter- (individual/human variation) movement variations on technique (Preatoni et al., 2013). Human MV is broadly defined as the normal variation in motor performance across multiple repetitions of the same task (Stergiou et al., 2006). MV is characteristic of human biological systems whereby individual repetitions of the same task will never be identical due to unique non-repetitive neural and motor patterns (Bernstein, 1967). Indeed, every athlete/individual possesses an array of motor, cognitive, and social actions that permit movement adaptability to changing environments and stimuli (Hadders-Algra, 2010). The movement(s) executed by an athlete/performer in response to a given stimulus are influenced by internal physiological processes (e.g. genes, ion channels, neuro-motor transmission, movement control) in addition to their perceived assessment of the environmental/situational context (e.g. opponents, weather conditions) and previous experiences unique to the individual (Bertenthal, Campos, & Kermoian, 1994; Farana, Irwin, Jandacka, Uchytil, & Mullineaux, 2015; Muller & Sternad, 2004). With experience and task-specific practice, prediction error can be gradually eliminated or minimized, thereby optimising the accuracy and efficiency of the movement pattern (Schmidt & Lee, 2005).

Until recently, MV was deemed undesirable system ‘noise/error’, evidence of dysfunctional movement patterns, and an aspect of performance that decreases as skill proficiency increases on the basis that unwanted degrees of freedom in the kinematic chain are eliminated (Bartlett, 2007; Bartlett, Wheat, & Robbins, 2007; Langdown, Bridge, & Li, 2012). Consequently, it was assumed by biomechanists that variance within sports techniques/movement patterns should be reduced in order to optimise the performance of a given task. Therefore, training should foster a singular, all-encompassing technical model (Bartlett, 2007; Newell & Corcos, 1993). However, recent studies have re-evaluated the role of MV and present biological variability as a desired functional change associated with the flexibility of the neuromusculoskeletal system to explore different strategies and adapt to the task/environment (Bradshaw et al., 2007; 2009; Keogh et al., 2007).

With regards to the analysis of human MV measures, time-continuous data analysis and discrete data analysis have been proposed within the literature (Komar, Seifert, & Thouvarecq, 2015). Time-continuous data analysis assists in defining the nature of MV within a single trial (i.e. intra-trial variability) by taking into consideration the order/sequence of predicted data points of a movement as well as the possibility of 'chaotic'/unpredictable movement behaviours (Fonseca, Diniz, & Araújo, 2014; Kuznetsov, Bonnette, & Riley, 2014). This may involve the employment of the approximate entropy (ApEn) which measures the expected outcomes of a time series/trial (Pincus, 1991; 2006) and recurrence quantification analysis which help to determine the repeatability and reoccurrence of dynamical systems over time (Kuznetsov, et al., 2014). The combination of these measures can help to understand the predictability of a time series/trial, observe how movement changes over time, and uncover irregular/complex time series patterns (Komar, Seifert, & Thouvarecq, 2015).

Meanwhile, discrete data analysis compares differences between multiple trials, conditions or individuals (inter-subject variability) by categorising movement profiles as opposed to distinguishing the nature of the MV (Komar et al., 2015). If a number of athletes complete the same movement/task under the same conditions or if an individual athlete completes many trials of the same task under identical conditions, movement profiles can be created based on kinetic and kinematic variables (Komar, Hérault, & Seifert, 2013; Seifert, et al., 2011). Discrete data analysis can be computed through the use of statistical methods including: 1) normalised root mean square which calculates mean variability and consistency of different instances of performance trials via time-angle plots (Chow, Davids, Button, & Koh, 2007; Hodges, Hayes, Horn, & Williams, 2005; Sidaway, Heise, & Schoenfelder-Zohdi, 1995); 2) Cauchy criterion which identifies the quantity and nature of variability by analysing movement patterns across space and time (Rein, 2012); 3) cluster analysis that merges movement data without knowledge of performer differences (e.g. gender, ability level) that allows for an unbiased grouping of performance trials across a large dataset (Komar et al., 2015); and 4) uncontrolled manifold that assists in determining the 'functional' variability of a task/movement by analysing the stability of a performance variable across multiple trials and how such variables compensate from trial-to-trial to ensure task/movement success (Rein, 2012; Scholz & Schöner, 1999).

A dynamical system theory (DST) approach has also been recommended with previous literature to quantify MV and potential constraints and/or trends that contribute to behaviours and influence movement (Colombo-Dougovito, 2016). DST assists in observing and explaining developmental trends and constitutive phases of movement according to three constraints (individual, task and environment) (Golenia, Schoemaker, Otten, Mouton, & Bongers, 2017). Understanding how these constraints interact with one another to create spontaneous behaviours (i.e. motor movement) and coordinative patterns can help to explain inter-subject MV (Colombo-Dougovito, 2016), identify different movement trends within a particular skill (Golenia et al., 2017), and characterise ranges of coordination patterns used to complete a movement/motor task (Preatoni et al., 2013). DST infers that MV plays a functional role in motor movement and may be useful in interpreting the range of possible patterns and transitions between the same or different motor tasks via two methods: (1) angle–angle plots; and (2) position–velocity plots (Preatoni et al., 2013). Angle-angle plots can help to identify coordination changes and relative coordinative invariances (Heiderscheit, Hamill, & Van Emmerik, 2002; Wheat & Glazier, 2006), whilst position–velocity plots detect the position and velocity of a joint or segment relative to each other that can help to characterise single joint or segmental joint coordination (Hamill, Haddad, Heiderscheit, Van Emmerik, & Li, 2006; Hamill, Van Emmerik, Heiderscheit, & Li, 1999; Van Emmerik et al., 1999).

Previous research has also endorsed more common methods of movement analysis, including 95% confidence intervals (95% CI) for case studies (n = 1) and root mean square difference (RMSD) for experimental studies with a small number of participants ($n \leq 5$) (Mullineaux, 2000). Furthermore, canonical correlation analysis has been recommended to examine of inter-trial variability across different time points of movement involving the upper-extremities and multiple degrees of freedom (DoF) (Krüger, Straube, & Eggert, 2017). Moreover, typical error (TEM), intra-class correlation coefficient (ICC), standard error of mean (SEM) or coefficient of variation (CV%) are also used to quantify MV across multiple performance trials, groups of individuals or testing occasions (Atkinson & Nevill, 1998; Hopkins, 2000). CV% is perhaps the most prevalent statistical measure utilised within the literature as it can be an effective way of determining both intra- and inter-individual MV (e.g. Hausdorff, Zemany, Peng, & Goldberger, 1999). Indeed, whilst traditional CV% analysis is practical for calculating and understanding degrees of inter- and intra-subject variability between movement trials (Preatoni et al., 2013), it may however contain variable percentages of both technological error (e.g. motion capture system arrangement, marker placement, environmental changes) and biological movement variability (BCV%) (i.e. unique non-repetitive neural and motor patterns - Rodano & Squadrone, 2002). Though the separation of technological error and BCV% is not needed when determining the reliability of performance measures, it is not ideal for the quantification of 'true' MV (Keogh et al., 2007). Consequently, previous research (Bradshaw et al., 2007; 2009; Farana et al., 2015; Keogh et al., 2007) proposed a method of estimating biological variability (BCV% = CV% - SEM%) via intra-individual analysis that accounted for technological error (SEM%) by subtracting the SEM% from the traditional CV% values. Indeed, Bradshaw et al. (2007) reported that traditional CV% analysis inflated MV measures by as much as 72% during the kinematic analysis of a sprint start, and subsequently, utilised SEM% to estimate any technological error/noise and traditional CV% to account for the summation of technological error/noise and MV. Such analysis has also been used to assess golf swings (Keogh et al., 2007), hand positions among gymnasts performing a 'round off' manoeuvre (Farana et al., 2015) and running (Queen, Gross, & Liu, 2006).

Within the current literature, evidence has demonstrated that experienced boxers exhibited intra- and inter-trial movement variance when punching (Orth, van der Kamp, & Rein, 2018). The authors concluded that this resulted from boxers manipulating their technique (via upper-limb kinematics and velocities) in order to adapt to their opponent and/or to ensure that their offensive manoeuvres were unpredictable. Conversely, Lenetsky et al. (2017) reported small-to-moderate within-subject variability for the impact kinetics of jab (12%), rear-hand cross (9.3%), lead hook (6.6%), and rear hook (7.7%) punches, respectively, among 'trained' boxers, compared to 'untrained' boxers (jab - 13.3%, rear-hand cross - 10%, lead hook - 9.3%, and rear hook - 9.4%). The authors concluded that the 'trained' boxers exhibited lower movement variance across all punch types due to their increased familiarity with the techniques subsequently leading to a decrease in movement ‘error’. Turvey (1990) states how MV is evident when punching due to the dynamic nature of opponents and training equipment utilised, such as punch bags, speed bags, and hand pads. Indeed, when punching a target, boxers must concurrently judge the distance to the target, select the specific technique to utilise, and assess how forcefully to perform the punch whilst the opponent/target is still within ‘punching range’ (Choi & Mark, 2004; Hristovski et al., 2006), suggesting MV might actually benefit performance.

The effect of distance on a boxer’s striking pattern has also been shown to change boxer’s technique/movement patterns and punch selection in relation to the location of the desired target (Hristovski et al., 2006). At greater distances, boxers favoured straight punches, whereas hooks and uppercuts were the punches of choice closer to the target. This highlights how a boxer’s perception of the targets’ relative position influences which punch is executed and over what trajectory (i.e. lead hook or lead uppercut at mid-range), with Davids et al. (2006) and Hristovski (2006) adding how a boxer’s arm segment dimensions (limb lengths), pre-fight strategy, fighting ‘style’, and perceived efficiency (perception of own performance capability) are factors. Furthermore, experience and skill level have also been shown to influence the consistency of actions and techniques across various sports comprising dynamic, full-body movements (Button et al., 2003; Hanford, 2006; Wagner et al., 2012). Consequently, the amalgamation of these variables foster high levels of intra- and inter-limb variability during punching (Davids et al., 2006; Seifert, Button, & Davids, 2013), and ought to therefore be appraised/considered during biomechanical analyses.

Given its role in sports performance and maximal punching in particular, it is surprising that MV has received limited attention to date. Also, given the unpredictability of opponents and the ballistic nature of maximal punching itself, high MV could provide boxers with purposeful solutions to what is a complex environment. The integration of internal (e.g. judging of distance, punch selection and force application) and external (e.g. technical strengths and weaknesses of the opponent, pre-fight strategies, and fighting 'style' of the opposing boxer) characteristics of competition suggests intra- and inter-limb variability during punching could enhance performance by affording boxers with opportunities to adapt their punching technique according to demands posed during competition (Davids et al., 2006; Orth et al., 2018; Seifert et al., 2013).

Recognising the degree of MV associated with different punch types will be valuable for identifying the occurrence of meaningful changes in maximal punching characteristics following technique- or strength-related interventions, allowing coaches and boxers to detect worthwhile training practice- and/or intervention-based changes in performance, and therefore, facilitate the monitoring of a boxer's progression (Hopkins, 2004; Hopkins, Hawley, & Burke, 1999; Preatoni et al., 2013).

2.4.7. Data collection and processing in punching biomechanics

In order for biomechanists to collect accurate data, make comparisons between participants and confidently test research hypotheses, a study must be designed and controlled effectively. Smith (2012) suggests that a suitable experimental design, data collection methods and processing procedures are essential to obtain data of a high quality, in addition to minimising potential threats to external and internal validity. Due to the high speed and dynamic nature of punching, data needs to be tracked, sampled and processed adequately to accurately capture the motion of the markers. Therefore, a comprehensive insight into the biomechanics of punching requires the combination of kinematic and kinetic data to quantify the motion and velocities of the upper-limbs, the forces produced by the lower-limbs and how these forces are distributed between the lead and rear leg during different punch types.

2.4.7.1. Motion capture

In recent years, boxing/punching kinematics have been assessed through the use of 3D motion capture systems (Cabral et al., 2010; Piorkowski et al., 2011) as opposed to 2D systems utilised in earlier research (Atha et al., 1985; Whiting et al., 1988). Although 3D motion capture analysis often restricts data collection to a laboratory setting (under unlikely conditions in comparison to actual competition), the positive aspects of this method (high image quality, comprehensive marker tracking, and high-speed data collection) arguably surpass its limitations in relation to external validity (Smith, 2012). Due to the ballistic nature of punching (which comprises considerable velocities and accelerations), a high video frame rate is essential to accurately capture kinematic data associated with such dynamic actions. Punch kinematics have been captured at frame rates between 200-250 Hz (Cabral et al., 2010; Cheraghi et al., 2014; Piorkowski et al., 2011) in boxing, and between 100-240 Hz in other combat sports (De Quel & Bennett, 2014; VencesBrito et al., 2011). It is difficult to know whether the sample rates used in previous research are sufficient to optimally capture the motion of maximal punching, which lasts between 50-300 ms (Aagaard et al., 2002; Cheraghi et al., 2014; Whiting et al., 1988), but it’s plausible to suggest that accurate kinematic measurements of maximal punches require a high frequency frame rate in order to sufficiently capture data with minimal noise interference. This suggestion can be related to the findings on baseball pitching by You, Siy, Anderst, and Tashman (2001) which propose a frame rate of 250 Hz is suitable for assessing the upper extremities of sporting movements performed at high speeds. Moreover, as a baseball pitch, from front foot contact to ball release, exhibits similar movement speeds to a punch (~150 ms, Stodden, Campbell, & Moyer, 2008), it is therefore reasonable to suggest that a capture frame rate of 250 Hz would be appropriate for analysing the kinematics of punching.

2.4.7.2. Force measurement devices

Within the body of literature concerning boxing, martial arts and combat sports in general, force platforms have been used sparingly to investigate the forces produced during punches. Considering the accuracy, clarity, ease of application, and in some cases portability of force platforms, this is somewhat surprising. Generally, force platforms within combat sport research have been used to test GRF associated with the punches of boxers (Mack et al., 2010; Su et al., 2013) and karatekas (Cesari et al., 2008; Gulledge et al., 2008).

In addition to GRF, force platforms have been adapted within research to assess the impact forces associated with punches (Loturco et al., 2016). Devices such as punch bag dynamometers utilising water displacement (Fritsche, 1978; Joch et al., 1981), a ballistic pendulum with a force transducer (Atha et al., 1985), a uni-axial strain gauge system (Karpilowski et al., 1994), punch bag-embedded accelerometers (Baagrev & Trachimovich, 1981; Broker & Crowley, 2002; Buśko et al., 2016), boxing-specific dynamometers (Čepulėnas et al., 2011; Dyson et al., 2005; 2007; Hlavačka, 2014; Smith et al., 2000; Smith, 2006), hybrid punch dummies (Viano et al., 2005; Walilko et al., 2005) and boxing glove-embedded force sensors (Chadli et al., 2014; Pierce et al., 2006) have also been utilised with varying degrees of accuracy. The diverse range of force measurement devices utilised in boxing-related punching research mean it is difficult to compare data on a study-by-study basis as very few studies tested their specific devices for validity and/or reliability. Consequently, the optimal measurement criteria for assessing the impact force of a boxer's punch are yet to be established.

2.4.7.3. Data smoothing and digital filtering

As previously alluded to, it is paramount that biomechanists utilise a high sampling rate when assessing motion/movements performed at high speeds. Previous research (Smith, 2012) suggests that dynamic motion should be sampled at a rate ten times greater than the highest anticipated frequency in the signal rather than the sampling theorem recommendation of using a sample rate twice that of the highest anticipated frequency (Challis, 2008). Once data has been collected, it is essential that it is smoothed (low-pass filtered) in order to eliminate any inaccuracy caused by random errors (noise) which can conceal the true values of interest (Challis, 2008). Noise is amplified when derivatives are calculated from raw displacement data and contaminates velocity and acceleration data. This is commonly achieved through the use of low-pass filtering which assists in eliminating any high-frequency noise and helps to 'smooth' data, which leaves the genuine signal unaffected to some degree (some noise will still remain in the signal). Various methods of data smoothing can be implemented, including: frequency domain techniques (e.g. Hatze, 1981), polynomial smoothing (e.g. Pezzack, Norman, & Winter, 1977), splines functions (e.g. Woltring, 1986) and digital filters (e.g. Butterworth filter - Winter, Sidwall, & Hobson, 1974), with the latter considered the ideal approach (Smith, 2012).

More specifically, low-pass Butterworth filters are common due to their simplicity and effectiveness at removing high frequency noise (Erer, 2007). Butterworth filters are able to separate time-displacement curve components of markers based upon whether the components are located above or below a selected cut-off frequency. This method, as with all filtering methods, leaves the true signal unaffected whilst accommodating noise located above and below the cut-off frequency (Milner, 2008; Sinclair, Taylor, & Hobbs, 2013). The selected cut-off frequency is paramount to the efficacy of kinematic analyses since if it is too low, the curve can become over-smoothed, and if too high, noise will still remain in the curve (Sinclair et al., 2013). Visual inspection has often been a method of determining the level of filtration that data is subjected to, although the repeatability and impartiality of this approach is questionable (Derrick, 2004). One effective method of data filtering is the use of residual analysis. Advocated by Winter (2009), residual analysis filters raw data at various cut-off frequencies and determines any residuals (differences between observed values and predicted values of a dependent variable) located between filtered and raw data. This assists biomechanists in selecting a pertinent cut-off frequency with the concession that signal distortion and level of noise are comparable. However, this method is not without issues with suggestions by previous authors that cut-off frequencies derived from residual analysis alone are generally too low, especially when a high sampling frequency is used, which may cause over-smoothing (Smith, 2012).

Accordingly, it is imperative that biomechanists are aware of how different smoothing processes and cut-off frequencies can influence raw data in order to select a suitable technique that will accurately smooth data without misrepresenting the true signal. For sporting actions that are explosive and dynamic in nature, it has been advocated that the selected cut-off frequency should be as high as possible in order to acquire accurate joint kinetic and kinematic data whilst minimising potential errors (Bezodis, Salo, & Trewartha, 2011).

Signal errors can occur as a result of various factors including surface marker movement, noise in GRF measurements, inaccurate joint models and inaccurate marker locations (Smith, 2012). Despite the wide array of potential errors, using applicable signal processing techniques can reduce the chances of errors influencing collected data whilst implementing cluster sets and global optimisation methods have also been suggested to assist in eliminating errors associated with incorrect marker locations (Rao, Amarantini, Berton, & Favier, 2006; Riemer, Hsiao-Wecksler, & Zhang, 2008).

2.5. Physical performance-related aspects of punching

2.5.1. Physical performance-related characteristics associated with maximal punching performance

Despite boxing commonly being termed informally as the ‘sweet science’, only since 2002 has research provided scientific evidence relating to the physical and physiological requirements of the sport (Arseneau et al., 2011). Prior to this, coaches and boxers were reliant upon trial and error approaches to training when attempting to augment technical skills and physical/physiological qualities (Bourne et al., 2002). Key physical performance-related characteristics of amateur boxing performance, such as strength and power (Loturco et al., 2016; Obmiński et al., 2011; Ramírez García et al., 2010), aerobic capacity (Arseneau et al., 2011; Bružas et al., 2014) and anaerobic threshold (Guidetti et al., 2002), in addition to comprehensive physiological profiles (Del Vecchio, 2011; Chaabene et al., 2015) have now been investigated. Prior to this contemporary body of research, boxers and coaches have often been reliant upon experimental approaches to training when attempting to augment technical skills and physical/physiological qualities. Nonetheless, there remains a lack of information with regard to maximal punching performance. Markovic et al. (2016) corroborates this notion by stating how knowledge of the function of specific muscle groups and/or body segments during punching still remains vague, hindering the optimal development of specific exercise interventions that can be implemented to enhance punching performance.

An examination of amateur boxing competition reveals that successful performance requires a boxer to possess a spectrum of physical and physiological characteristics. In particular, the ability to punch at maximal intensity necessitates a boxer be able to demonstrate a multitude of these physical traits simultaneously across the scheduled 3 x 3-minute rounds at elite level. It therefore seems imperative the various physical performance-related characteristics associated with maximal punching are firstly understood and then subsequently enhanced through sport-specific training interventions (Bishop, 2008; Čepulėnas et al., 2011). Based upon current evidence, the principal physical performance-related traits influencing maximal punching performance comprise muscular strength and muscular power.

2.5.1.1. Muscular strength

Described as the ability of the neuromuscular system to produce force against external resistance (Stone, Stone, & Sands, 2007), muscular strength is an essential physical performance-related characteristic of successful sports performance (Bompa & Carrera, 2005), particularly in contact sports (McMaster, Gill, Cronin, & McGuigan, 2014). Muscular strength, when expressed maximally, denotes the greatest application of force during a single maximal muscular contraction and forms an essential part of dynamic movement and motion, especially those observed within combat sports (James et al., 2016a). Despite the mechanics of punching and the technical competency of a boxer being vital components of punching force and velocity production (Hickey, 1980), enhancing a boxer’s maximal strength can influence additional physical attributes pertinent to boxing competition. Such attributes include punch power (Čepulėnas et al., 2011; Del Vecchio et al., 2019; Hlavačka, 2014), punch impact force (Loturco et al., 2016), punch acceleration (Loturco et al., 2014), punch velocity (Dengel et al., 1987; Solovey, 1983), and muscular power (Cormie, McGuigan, & Newton, 2011a). Moreover, muscular strength is strongly associated with force-time characteristics (rate of force development (RFD); external mechanical power) alongside general (e.g. jumping; sprinting; throwing) and sport-specific skill performance (Suchomel et al., 2016).

Muscular strength of both the upper and lower limbs is imperative to success in boxing and regarded as an essential component of punching performance (Chaabene et al., 2015; Loturco et al., 2014). It can be further dissected into absolute and relative strength, both of which play a role in combative sport. Absolute strength is regarded as the peak voluntary force produced during a maximal muscular contraction regardless of body mass, whereas relative strength signifies the amount of force generated by an athlete, divided by their body mass (Stone, Sands, & Pierce, 2005). Subsequently, due to amateur boxing being a weight-governed sport, relative muscular strength is arguably of greater importance than absolute muscular strength. Therefore, as relative strength can be considered as a critical component of boxing performance facilitating force production and positively influencing other physical traits, understanding how to enhance a boxer's strength-to-body mass ratio is essential.

Muscular strength (both isometric and dynamic) is influenced by an athlete's neural drive efficiency (McBride, Triplett-McBride, Davie, & Newton, 2002), intermuscular coordination (Sale, 2003) and cross-sectional area (Narici, Roi, Landoni, Minetti, & Cerretelli, 1989). There exists strong evidence that maximal muscular strength is a key discriminator of successful combat sport performance (i.e. stronger fighters are generally more successful than weaker combatants) (James et al., 2016a; 2016b), with attempts having been made to determine the importance of both isometric (Guidetti et al., 2002; Khanna & Manna, 2006; Loturco et al., 2016; Ramírez García et al., 2010) and dynamic muscular strength (Loturco et al., 2014) to punching performance. Guidetti et al. (2002) reported a strong correlation (r = 0.87) between hand grip strength, boxing competition ranking, and competitive success among amateur boxers. Comparably, the hand grip dynamometer strength test was proposed by Ramírez García et al. (2010) and Čepulėnas et al. (2011) to be a suitable method of monitoring muscular strength adaptations in amateur boxers. Similarly, Khanna and Manna (2006) suggested that isometric grip and upper back strength are important as both variables positively affect the forcefulness of punches and can diminish upper extremity injury risk. Loturco et al. (2016) highlighted a correlation between lower-body isometric muscular strength and straight punch impact forces in elite amateur boxers, with jab (*r* = 0.68-0.69) and rear-hand cross (*r* = 0.73-0.83) impact forces strongly associated with maximal isometric strength on the half-squat exercise in 15 elite amateur boxers.

However, isometric strength measures are reported to seldom correlate with explosive/dynamic performance (Anderson et al., 1991; Coulson & Archer, 2015; Rutherford & Jones, 1986; Tanner & Gore, 2013), particularly with reference to striking in combat sports (James et al., 2016a). Indeed, the limited movement specificity and disparate motor unit activation patterns between isometric and dynamic/explosive actions means velocity-based measures of performance (e.g. joint velocities) are not adequately associated with isometric strength measures (Wilson et al., 1995). Therefore, as dynamic tests provide a better illustration of the dynamic components comprising athletic performance (Frost, Cronin, & Newton, 2010), it appears that assessing strength dynamically provides a better representation of the influence of muscular strength upon punching performance, particularly for the upper-body (Loturco et al., 2016).

Despite the use of isometric strength tests, Loturco et al.'s (2016) suggestion that an association exists between lower-body muscular strength and force production capabilities in relation to maximal punching performance is supported by findings within previous research. Various authors (Cheraghi et al., 2014; Filimonov et al., 1985; Lenetsky et al., 2013; Turner et al., 2011) noted how the generation of force via lower body triple extension (hip, knee and ankle) is critical to the degree of force transmitted by the fist upon impact with a target. Meanwhile, the lack of a relationship between upper-body strength and punching force could be deemed surprising, especially considering prior recommendations to enhance this trait within previous literature (Chaabene et al., 2015; Ruddock, Wilson, Hembrough, & Winter, 2016;

Turner et al., 2011). Previous research has also illustrated that a positive relationship exists between dynamic muscular strength and punch acceleration. Loturco et al. (2014) established muscular strength on bench press and squat machine assessments correlated (*r* = 0.65-0.79) with straight rear-hand punch acceleration across all karatekas for all punch trials. The authors concluded both upper- and lower-body maximal strength was predictive of punching acceleration across all punch conditions, suggesting that augmenting both upper-body and lower-body maximal muscular strength could promote increases in punching performance.

2.5.1.2. Muscular power

Muscular power is important to successful performance across various sports (Cormie et al., 2011b), particularly amateur (Chaabene et al., 2015; Lenetsky et al., 2013) and professional (Halperin, Hughes, & Chapman, 2016b) boxing. Determined as the product of force and velocity during a maximal effort muscular contraction (the degree of muscular power produced) is dependent upon their neuromuscular system’s efficiency at recruiting motor units, the speed at which sarcomere within the utilised musculature shortens, and the external load applied (James et al., 2016a; Suchomel et al., 2016). The greater the external load, the greater the degree of force required to perform ballistic/explosive motions, meaning velocity decreases as load increases (Cormie et al., 2011a). Consequently, muscular power is governed by a continuum that encompasses forceful actions with high loads (i.e. grappling/wrestling) and velocity-based motion with minimal loads (i.e. striking) at opposing ends (Figure 2.7) (James et al., 2016a).

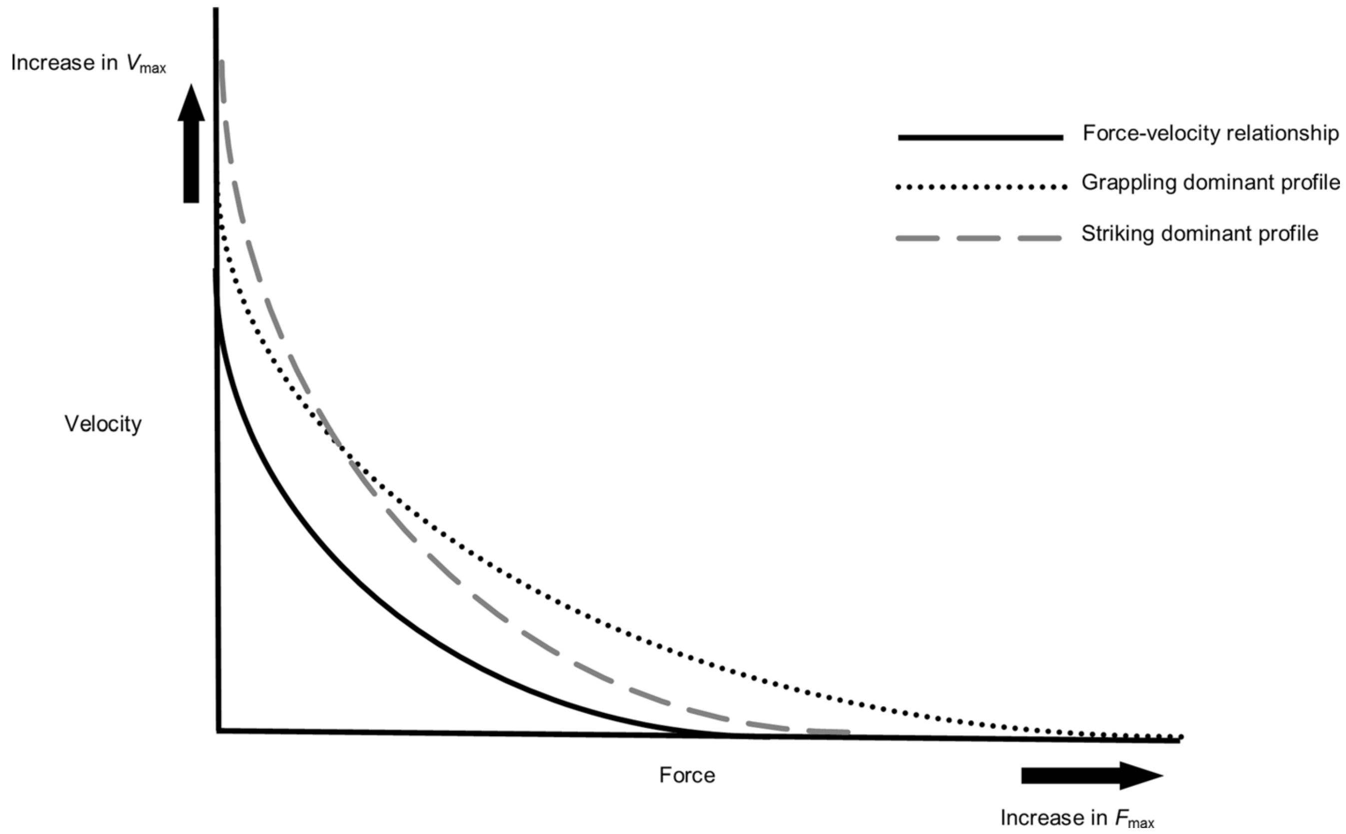

Figure 2.7. Example power profile of mixed martial arts competitors based upon combat sport history and dominant strategy using the force-velocity curve continuum (V_{max} = maximal velocity; F_{max} = maximal force - James et al., 2016a; p. 1543).

As the action of punching is extremely dynamic, high-level boxing performance requires considerable levels of muscular power in both the upper and lower limbs to optimise punching performance (Chaabene et al., 2015). Therefore, successful punching is often dependent upon the ability to generate force rapidly in response to an observed or anticipated stimulus during competition. The rapid generation of force is often classified as rate of force development (RFD) and is essential to striking within combat sports (Tack, 2013). RFD characterises the greatest slope across the force-time curve (Wilson & Murphy, 1996) and accurately reflects the dynamic nature of athletic performance (Frost et al., 2010). In relation to boxing, a competitor is only able to manipulate resultant force by influencing the acceleration of the movement given mass remains unchanged during performance (Thomson, 2016). Aagaard et al. (2002) and Cheraghi et al. (2014) identify RFD as being essential within boxing with successful punches (i.e. punches that strike the intended target) having an execution time between 50-300 ms. Meanwhile, other research noted single punch execution times between 553-716 ms (jab - 587 ± 166 ms; rear-hand cross - 553 ± 211 ms; lead hook - 570 ± 168 ms; rear hook - 716 ± 305 ms) (Piorkowski et al., 2011). As human musculature is unlikely to produce a maximum force within 300 ms (Aagaard et al., 2002), the use of RFD assessments would appear useful for boxers seeking to assess their rates of force production capabilities. However, it is crucial that RFD assessments are as sport-specific as possible, unlike to the often utilised isometric tests, which as previously alluded to, have a limited relationship to dynamic athletic performance (Murphy & Wilson, 1996). Boxing-specific RFD assessments have been completed within previous research (Obmiński et al., 2011), establishing how shot put distance using a 4 kg medicine ball/put strongly correlated (r = 0.83) with the force of rear-hand cross punches in experienced Polish boxers.

In addition to RFD, previous research has also highlighted how boxers instinctively utilise the stretch-shortening cycle (SSC), particularly at the elbow and shoulder joints, during rear-hand cross (Cheraghi et al., 2014), jab, lead hook and rear hook punches performed at maximal intensity (Piorkowski et al., 2011). Comprising a forceful concentric muscular contraction following a rapid eccentric contraction of agonist muscles (Bartlett, 2007; Komi & Nicol, 2010), the SSC underpins punching among elite mixed martial artists (McGill et al., 2010). McGill et al. (2010) highlighted the existence of a relation phase separated by a 'double peak' in muscular stiffness/tension of the trunk musculature at both the initiation of a punch and at impact with a target (referred to as a contraction-relaxation-contraction sequence). This 'pre-loading' of specific musculature causes a rapid bout of muscular tension, leading to a more forceful punch whilst also maximising the acceleration path towards the opponent/target (Cheraghi et al., 2014; Yessis, 1994).

Contemporary research has established how lower-body muscular power is strongly associated with punch impact force among elite amateur boxers (Loturco et al. 2016) and punch impact power among amateur combat athletes (Del Vecchio et al., 2019). Furthermore, the same authors also noted similar associations regarding upper- and lower-body power and punch acceleration among elite karatekas, respectively. Interestingly, the authors determined up to 65% of the variation in punch acceleration could be explained via strength and power parameters, with technical competency accounting for the remaining variation. This was corroborated by Loturco et al. (2016) whereby vertical jumping ability (squat jump (SJ); counter movement jump (CMJ)) was accountable for ~75% of force magnitudes exhibited by elite boxers during maximal jab and rear-hand cross punches. The conclusions of Loturco et al. (2016) corroborate the view of Chaabene et al. (2015) that successful boxing performance requires competitors to demonstrate considerable upper- and lower-body muscular power to optimise punching performance. This is particularly important given this physical trait is strongly associated with the kinematic and kinetic characteristics of jabs and rear-hand crosses, the most prevalent punch types observed within competitive boxing (Davis et al., 2013; 2015; 2018; Slimani et al., 2017). It is therefore likely that, technical skills aside, boxers possessing superior levels of muscular power have a greater likelihood of causing damage to their opponent, reinforcing the need for them to train such qualities.

2.5.1.3. Speed

Speed is defined as distance divided by time and can refer to the movement of a body part such as the hand in boxing or to a whole-body movement such as sprinting (Young & Sheppard, 2011). Coulson and Archer (2015) assert how both upper- and lower-limb speed are essential components of boxing as the act of punching requires dynamic whole-body coordination, suggesting the ability for the upper-limbs to rapidly reach peak speeds following the application of force by the lower-body is critical to successful punching (Cheraghi et al., 2014). Coaching texts often refer to speed being the primary attribute that makes the difference between winning and losing a contest, regardless of a boxer’s fighting style or technique (Barnes, 2005), though this statement is yet to be formally addressed in the scientific literature. Verkhoshansky and Siff (2009) state successful performance in boxing is reliant on the speed of technique execution as boxers need to achieve peak upper-limb speeds rapidly in order to land successful, damaging strikes (Adamczyk & Antoniak, 2010). Previous research has noted the faster a punch is executed, the greater its knock-out potential resulting from the total impact kinetic energy of the strike being exponentially associated to its speed (La Bounty et al., 2011). Indeed, speed plays a supporting role to muscular power production based upon the force-velocity relationship (F-V) and the ability to produce high degrees of force in minimal time, such as punching (Cormie et al., 2011a).

2.5.2. Physical performance-related measurement methods

2.5.2.1. Muscular strength

The most common practices for determining muscular strength are through the use of maximal voluntary contractions for isometric strength and/or one-repetition maximum (1RM) tests for dynamic strength. Isometric tests are commonly performed utilising dynamometers, cable tensiometers or strain gauges which have all demonstrated good reliability in both single and multi-joint test protocols (Wilson & Murphy, 1996).

In terms of dynamic muscular strength, 1RM tests utilising multi-joint free weight exercises are most commonly observed, whereby a maximum strength score is achieved once an athlete is unable to complete a lift at a certain load or cannot complete a lift with correct technique. The benefits of utilising 1RM assessments are that muscular strength can be established under dynamic conditions in movements potentially similar to those performed in competition, a feat that is challenging to replicate with isomeric strength tests (Tanner & Gore, 2013). Moreover, the 1RM test itself has proven to be reliable in quantifying the level of dynamic muscular strength (Seo et al., 2012), and due to the dynamic nature of punching, 1RM assessments appear more appropriate than isometric assessments for boxers and other combat athletes that utilise striking techniques.

The most commonly observed 1RM exercises utilised within research to assess the maximal strength of the upper- and lower-body are the bench press and back squat. These exercises have been shown to be reliable measurements for 1RM testing (Flansbjer & Lexell, 2010; Levinger et al., 2009; Tagesson & Kvist, 2007), with bench press test-re-test intraclass correlation coefficients (ICC) of 0.94-0.99 (Bellar et al., 2011; Rhea, Ball, Phillips, & Burkett, 2002; Senna et al., 2016) and 0.7-> 0.9 for the back squat (Augustsson & Svantesson, 2013; Comfort & McMahon, 2014; Ritti-Dias et al., 2011; Soares-Caldeira et al., 2009).

2.5.2.2. Muscular power

Muscular power is commonly reported as either a peak or mean value within the literature. Peak power documents the maximum power value immediately achieved during a forceful action (Dugan et al., 2004) whereas mean power is typically noted as the average of sampled time points usually taken from the initiation of the concentric phase of a lift until the point at which peak power occurs (James et al., 2016a). In order to optimally assess muscular power, it is recommended peak power scores be documented using ballistic actions that minimise any form of deceleration as peak power data demonstrates superior correlations to ballistic performance in comparison to average power data (Dowling & Vamos, 1993; Dugan et al., 2004; Harmen, 1990). Furthermore, ballistic actions provide the greatest power outputs compared to other exercises/movements (Newton et al., 1996). Consequently, ballistic exercises are commonly utilised to quantify the components of muscular power for both the upper- and lower-body.

Within combat sports, upper-body muscular power has predominantly been assessed using the bench press throw (da Silva, Simim, Marocolo, Franchini, & da Mota, 2015; Drid et al., 2015), traditional bench press (Fagerlund & Häkkinen, 1991; García-Pallarés, López-Gullón, Muriel, Díaz, & Izquierdo, 2011; Roschel et al., 2009) or a combination of both exercises (Loturco et al., 2014; 2016) using various loads across the force-velocity curve. The bench throw assessment is considered to be a reliable and valid test for measuring upper-body muscular power (Alemany et al., 2005), with a loading parameter of 30% 1RM seeming to be the most effective at inducing peak power output (Alemany et al., 2005; Falvo et al., 2006; Newton et al., 1997; Thomas et al., 2007), particularly among karatekas (Roschel et al., 2009). In combat sport athletes, loads of around 30% 1RM are suggested to be more effective than higher loads (e.g. 60% 1RM) as a result of velocity-based power being more important than force-based power in order to land effective strikes (James et al., 2016a; Roschel et al., 2009). It is likely this argument can be made for boxers in particular, although the new rules of amateur boxing encourage the use of forceful punches whilst karate still uses a point-based system that promotes the use of single strikes executed at high velocity. It has also been suggested that upper-body power can also be tested reliably through the use of field-based tests, such as various medicine ball throws (Harasin, Dizdar, & Markovic, 2006; van den Tillaar & Marques, 2013) and, more specifically to boxing, shot putting (Obmiński et al., 2011).

For the assessment of lower-body muscular power, loaded jump squats (Loturco et al., 2014; 2016) and back squats using various loads across the force-velocity curve (García-Pallarés et al., 2011; Loturco et al., 2014; Roschel et al., 2009) are prevalent within the combat sport literature. Additionally, ballistic bodyweight exercises such as SJs (Fagerlund et al., 1991; Loturco et al., 2014; 2016; Roschel et al., 2009; Tabben et al., 2014) and CMJs (Drid et al., 2015; Loturco et al., 2014; 2016; Tabben et al., 2014) have also been used to assess lower-body power effectively. Similar to the bench throw, the loaded jump squat is a reliable test for the assessment of lower-body muscular power (Alemany et al., 2005). Research has reported peak power in the jump squat is achieved at loads equating to 0% of an athlete's 1RM (i.e. bodyweight with no added external load) (Bevan et al., 2010; Cormie et al., 2008; Dayne et al., 2011; Jimenez-Reyes et al., 2015). However, it has also been suggested peak power occurs at various loads across the force-velocity continuum ranging from 10% 1RM (Stone et al., 2003), 20% 1RM (Turner, Unholz, Potts, & Coleman, 2012), 30% 1RM (Alemany et al., 2005), 48-63% 1RM (Baker, Nance, & Moore, 2001), 60% 1RM (Alcaraz, Romero-Arenas, Vila, & Ferragut, 2011), 50-80% RM (Sleivert, Esliger, & Bourque, 2002) and 80% 1RM (McBride, Haines, & Kirby, 2011) in the jump squat. Such variance may stem from the varying athletic populations used to quantify these peak power percentages, with the higher 1RM loads likely producing peak power in contact sport athletes (i.e. rugby league players, American football players), and the lower 1RM loads suiting athletes who do not have to overcome external loads/inertia as part of their sport (e.g. track and field competitors). This therefore suggests that lighter 1RM loads may be more suitable for quantifying jump squat peak power of amateur boxers.

In order to quantify an athlete's expression of power during ballistic exercises such as the jump squat and bench throw, the use of field-based testing devices is now common practice in the absence of laboratory equipment. Tri-axial accelerometers are prevalent having been demonstrated to be valid and reliable for estimating both lower

(Bampouras, Relph, Orme, & Esformes, 2013; Bubanj et al., 2010; Castagna et al., 2013) and upper-body (Comstock et al., 2011) power. Additionally, the use of a single linear position transducer (LPT) also provides valid and reliable estimations of power (Crewther et al., 2011; Cronin, Hing, & McNain, 2004; Drinkwater, Galna, Mckenna, Hunt, & Pyne, 2007). Of the options available to a researcher, it appears tri-axial accelerometers are the optimal choice given their high reliability and validity alongside their ability to measure both upper- and lower-body power accurately.

In terms of laboratory-based assessments, it is common to see the use of rotary encoders to measure muscular power. Rotary encoders are devices that attach to conventional RT equipment (e.g. a barbell) which then utilise a rotating wheel tether to convert motion (i.e. speed of movement) into an analogue reading (Fernandes, Lamb, & Twist, 2016; Jennings, Viljoen, Durandt, & Lambert, 2005). Rotary encoders have been used to measure muscular function (Fry, Schilling, Weiss, & Chiu, 2006), muscular power (Jennings et al., 2005) and bar velocity (Stock, Beck, DeFreitas, & Dillon, 2011), whilst also demonstrating reliability when assessing both upper-body (ICC = 0.97; 95% CI = 0.95-0.98) and lower-body (ICC = 0.97; 95% CI = 0.95-0.98) power (Jennings et al., 2005). Consequently, the use of laboratory and/or field-based assessments provides the opportunity to accurately quantify muscular power among athletes.

2.5.2.3. Speed

Sprints over a short distance (i.e. 10 m) from a standing start are reported to accurately represent maximum speed capabilities of athletes (Young et al., 2008; Young, Benton, & Pryor, 2001), with maximal linear sprints using fixed distance protocols being a reliable method of quantifying this physical trait (Hopker et al., 2009). The optimal method of recording sprint time is through the use of electronic timing gates that employ post-processing, which subsequently remove any 'false' signals (Earp & Newton, 2012). These false signals occur when the beam of the photocell is broken by an extended limb, instead of the torso, resulting in significant errors (Cronin & Templeton, 2008; Darrall-Jones, Jones, Roe, & Till, 2016).

Research pertaining to the assessment of maximal speed and/or acceleration among boxers and other combat athletes is scarce. Previous papers have examined the sprint speed of taekwondo combatants utilising 20 m (3.53 ± 0.35 s - Cetin, Keçeci, Erdoğan, & Baydar, 2009; 3.7 ± 0.2 s - Markovic, Misigoj-Durakovic, & Trninic, 2005), 30 m (5.07 ± 0.39 s among medal winners; 5.26 ± 0.48 s among non-medal winners - Sadowski, Gierczuk, Miller, & Cieśliński, 2012), and 6-s distance tests (40.18 ± 6.02 m - Suzana & Pieter, 2009). Additionally, sprinting performance of karatekas over 10 m (1.80 ± 0.05 s for kumite competitiors; 1.86 ± 0.07 s for kata competitors - Koropanovski et al., 2011) and 8-s (Baker & Davies, 2006) has also been documented. The results of taekwondo competitors over 20 m are lower than those observed across athletes in other sports such as rugby union (3.29 ± 0.2 s - Fletcher & Jones, 2004), rugby league (3.14 ± 0.12 s - Newman, Tarpenning, & Marino, 2004), soccer (3.11 ± 0.13 s - Newman et al., 2004), and track and field athletes (3.28 ± 0.46 s - Winchester, Nelson, Landin, Young, & Schexnayder, 2008). Additionally, the performance of karatekas over a 10 m distance is inferior to those achieved by highly trained athletes (1.68 ± 0.05 s - Turki et al., 2012). Unfortunately, no previous studies have examined the speed of boxers (via sprint assessments), meaning it is not currently known if this physical quality is associated with punching biomechanics and overall boxing performance. Though previous research has revealed the speed of the fist during a punch is influential to the force of the strike (Bolander et al., 2009; McGill et al., 2010), no research has evaluated the speed characteristics of boxers. Therefore, the influence of this physical quality on punching performance remains unknown, suggesting further research is required to determine whether speed assessments using sprint tests (10 and 20 m) correlate with specific biomechanical characteristics of punching, such as fist velocity and GRF.

2.6. The scientific process in boxing performance: The influence of, and associations between, biomechanical and physical performance-related qualities.

Given the complex and multifaceted nature of competitive boxing, success in the sport is clearly dependent upon numerous variables with many features studied previously (see Figure 2.8). Though access to such studies is clearly helpful in determining the characteristics of a successful boxer (and their performances), the descriptive, cross-sectional nature of such research is unlikely to impact on applied practice (Bishop, 2008). For example, that isometric muscular strength tends to be higher in elite rather than sub-elite standards (James et al., 2017), does not mean improving this variable enhances the ability of the boxer, nor does it reveal the most effective means by which a boxer might enhance this property. According to the ‘Applied Research Model for the Sport Sciences' (Bishop, 2008), the translation of research to practice is facilitated by a step-by-step approach to research problems whereby predictors of performance and the efficacy of interventions should follow descriptive studies; to date, a clear majority of studies in boxing have only described the features of preparation (e.g. weight-making practices) and competition (e.g. punches thrown) in isolation.

Though research has moved beyond mere description revealing some associations between muscular strength and power and impact biomechanics of maximal punches, including punch force (r = 0.67-0.85; Loturco et al., 2016), punch acceleration (r = 0.63-0.80; Loturco et al., 2014), and punch power (r = 0.58; Del Vecchio et al., 2017), the multifaceted nature of boxing means there is much still to discover. Nevertheless, these relationships highlight how biomechanical and physical qualities integrate to enhance punching performance alongside other boxer-specific and competition-based characteristics that amalgamate to optimise overall boxing performance (see Figure 2.8). Taken together, it appears augmenting the biomechanical and/or physical performance-related qualities of maximal punches via targeted interventions (e.g. RT) may enhance maximal punching, and potentially, overall boxing outcome.

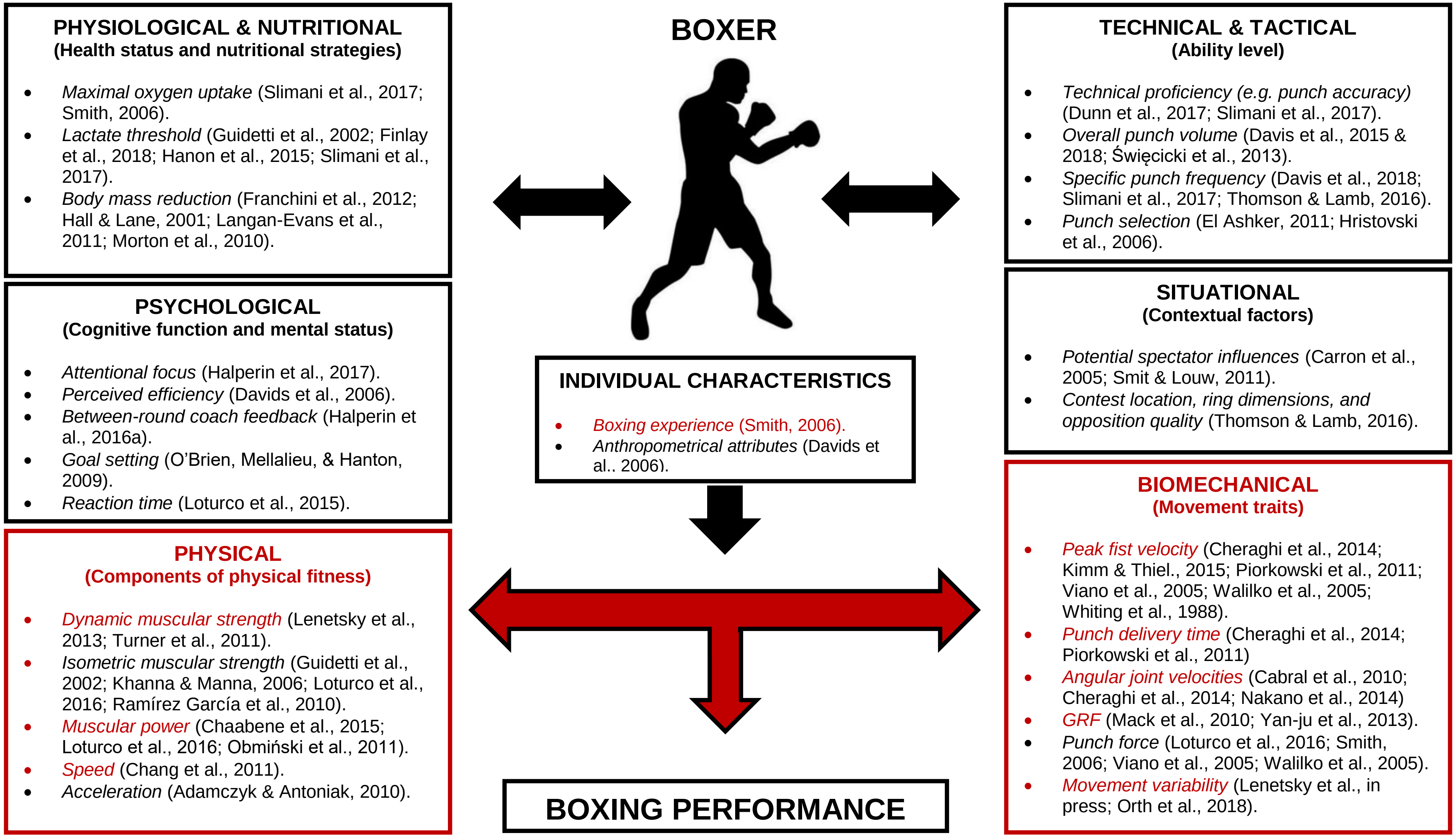

Figure 2.8. Overview of research themes associated with successful amateur boxing performance. Red ink denotes performance characteristics the current thesis will appraise in relation to maximal punching performance.

2.7. Resistance training in boxing

RT is a generic term that encompasses a wide array of different approaches that utilise a form of external load (e.g. free weights, resistance machines) to augment muscular and/or neuromuscular capabilities. RT often plays a central role in the physical preparation of athletes looking to enhance performance within their sport (Young, 2006). When implemented appropriately into an athlete's training regimen, RT can enhance a spectrum of physical and physiological traits responsible for successful sports performance, such as muscular strength, muscular power, muscular endurance, speed, agility and flexibility (Bompa & Haff, 2009; Verkhoshansky & Verkhoshansky, 2011). The most common method of introducing RT into a training programme is through the use of free weights. Free weights (comprising weighted barbells and dumbbells) allow athletes to train movement patterns similar to those experienced during competition and produce 43% greater muscle activity compared to the use of resistance machines (Schwanbeck, Chilibeck, & Binsted, 2009).

To achieve optimal improvements in performance, it is suggested a combination of general and sport-specific RT methods be utilised to develop all the neuromuscular factors contributing to the skills required for the chosen sport (Cronin, McNair, & Marshall, 2001; DeRenne, Kwok, & Murphy, 2001; Young, 2006). The specific method(s) and objective(s) of RT will influence the neuromuscular, physiological and morphological adaptations experienced by an athlete, with sport-specific movements (such as punching) being enhanced with the correct programme (McMaster et al., 2014).

2.7.1. Prominent resistance training methods

2.7.1.1. Strength training

Termed as the ability to produce maximal force against resistance (Kraemer & Ratamess, 2004), strength training (ST) is a highly effective method of stimulating increases in muscular strength (Cormie et al., 2011a; Folland & Williams, 2007), rate of force development (RFD) (Zatsiorsky & Kraemer, 2006) and mechanical power (Suchomel, Nimphius, & Stone, 2016). ST is augmented through the use of weighted equipment, such as free-weights, with optimal adaptations achieved when utilising loads >85% 1RM which have been shown to improve athletic ability through enhanced force-production resulting from both biochemical and morphological changes. These changes include elevated central nervous system (CNS) stimulation, enhanced motor unit recruitment and the inhibition of Golgi tendon organs (GTO) (Bompa, Di Pasquale & Cornacchia, 2003; Gabriel, Kamen, & Frost, 2006; Häkkinen, 1989).

The use of ST has been shown to have a positive influence on the RFD characteristics of athletes across various sports with several studies (Aagaard et al., 2002; Anderson et al., 2010; van Cutsem & Duchateau, 2005; van Cutsem, Duchateau, & Hainaut, 1998) highlighting these improvements, and further research demonstrating how maximal muscular strength may account for as much as 80% of the variance in voluntary RFD (150-250 ms) (Andersen & Aagaard, 2006). In support of these findings, a number of studies have examined the relationships between muscular strength and RFD (Haff et al., 2005; Kawamori et al., 2005; 2006; Kraska et al., 2009; Thomas, Jones, Rothwell, Chiang, & Comfort, 2015) with stronger individuals typically more able at generating greater RFD than weaker individuals. In addition to power characteristics, heavy-RT produces superior muscular strength adaptations compared to other RT methods (Stone, Stone, & Sands, 2007). As muscular strength is not developed through boxing skills training alone, boxers should use very high loads (> 85% 1RM) and low repetitions (< 5) when performing ST to enhance neuromuscular qualities related to punching performance (maximal strength; RFD; peak power) without the acquisition of excessive muscular hypertrophy (Fleck & Kearney, 1993; Turner et al., 2011; Verkhoshansky & Siff, 2009; Young, 1993). Consequently, athletes should endeavour to enhance their maximal strength levels to their greatest capacity within the context of their sport, including body mass restrictions often observed within combat sports (Suchomel et al., 2016).

As boxers commonly aim to compete at the lightest weight category possible, the strategies and techniques used to 'make weight' can play a critical role in the performance of a boxer during both training and competition, in addition to their general health (Franchini, Brito, & Artioli, 2012). It is not uncommon for boxers to lose body mass through methods such as acute energy restriction, severe dehydration and excessive exposure to heat (i.e. saunas and/or hot baths), which can have drastic effects on strength/power performance and overall health (Hall & Lane, 2001; Morton et al., 2010). The magnitude of body mass reductions observed has been highlighted in previous research, with boxers commonly losing around 3-4 kg the week prior to a contest (Hall & Lane, 2001). Such acute weight loss and dehydration can significantly impair various physical traits essential to combat sport performance, including punch force (Smith et al., 2001) and muscular strength and power (Roemmich & Sinning, 1996). Indeed, previous studies have reported muscular strength (13.6% - Gulati, Wasuja, & Kumari, 2006) and peak power (elbow flexion; 125.8 ± 0.3 W; elbow extension - 132.7 ± 8.4 W; Roemmich & Sinning, 1996) decreases among combat sport athletes after acute weight loss, highlighting the negative impact of this practice on important physical qualities associated with maximal punching performance. However, Morton et al. (2010) demonstrated that with the correct strategy, boxers can reduce body mass considerably (9.4 kg) and maintain muscular strength without acute losses in lean body mass. Consequently, boxers need to ensure that their weight-making strategies are not too radical so that physical performance remains unaffected.

2.7.1.2. Olympic weightlifting

Consisting of two exercises known as the 'snatch' and the 'clean and jerk', Olympic weightlifting (OL) movements are popular within the RT programmes of athletes due to their effectiveness at enhancing triple extension, a movement pattern observed across a plethora of sporting movements (Hori, Newton, Nosaka, & Stone, 2005). The two exercises that comprise OL involve raising a loaded barbell above the head in either one stage (snatch) or two stages (clean and jerk). As a result, Olympic lifts facilitate the development of whole-body muscular power (Cormie et al., 2011b; Schilling et al., 2002).

OL and its derivatives (e.g. hang clean, hang snatch, high pull) could be useful within a boxing-specific RT programme as a successful 'lift' requires the boxer to demonstrate considerable force and power characteristics (Fleck & Kearney, 1993; Ruddock et al., 2016; Turner et al., 2011). The ability to lift high loads at speed, such as with OL movements, augments an athlete's explosive power and RFD that transfers to various sporting actions, particularly striking within combat sports (Souza-Junior et al., 2015; Turner et al., 2009a). Consequently, the nature of OL in addition to their movement similarities across numerous athletic endeavours highlights their effectiveness as a method of power training (Cormie et al., 2011b).

2.7.1.3. Ballistic training

Ballistic training (BT) is defined as performing movements requiring rapid acceleration against resistance whereby the body or object achieves full acceleration (Turner, 2009a). The effectiveness of BT at enhancing RFD lies in the nature of the exercises that comprise this method of RT (e.g. bench throw; jump squat) which permit maximal acceleration throughout the entire movement to the point of projection (Turner et al., 2011). As a result of the ability to continue accelerating throughout the range of motion, concentric velocity, force, power and muscle activation are higher during a ballistic movement in comparison to a traditional RT exercise comprising a similar movement pattern (Cormie et al., 2007b; Newton et al., 1996). Training with ballistic exercises can enhance power production, enhance RFD, elevate neural activation and increase inter-muscular coordination that is specific to movements typically encountered in sports (Cormie et al., 2007a; Kyröläinen et al., 2005; McBride et al., 2002).

As BT is effective at enhancing the first 200-300 ms of the force-time curve (Häkkinen, Komi, & Alen, 1985; Newton & Kraemer, 1994), the use of this RT method, which increases RFD, is essential to optimising performance in boxing (Del Vecchio, 2011) whereby forceful punches occur between 50-300 ms from the initiation of motion to contact with the intended target (Aagaard et al., 2002; Whiting et al., 1988). The performance enhancements of BT in relation to boxing can be observed within the research of Obmiński and Wiesław (2012) which discovered how performing daily shot putt exercises across a 2-week period produced significant improvements in explosive strength in a movement pattern similar to that of a rear-hand cross punch in female boxers.

2.7.1.4. Plyometric training

Plyometric training (PT) is a popular method of dynamic RT among athletes striving to enhance muscular power and explosiveness (Chu, 1998). PT takes advantage of the stretch-shortening cycle (SSC) through the use of a quick eccentric contraction that is immediately followed by a rapid concentric contraction with a minimal amortisation phase (Davies, Riemann, & Manske, 2015). Plyometric exercises that encompass various medicine ball throws and jumping movements, are a highly effective RT method for augmenting muscular power and velocity, increasing peak force, RFD, elevating muscle activation and increasing an athlete's ability to utilise stretch reflexes (de Villarreal, Requena, & Newton, 2010; Hill & Leiszler, 2011; Jarvis, Graham-Smith, & Comfort, 2016; Vissing et al., 2008; Wilson & Flanagan, 2008). A further aspect of PT particularly useful to boxers who compete in weight-governed bouts is that increases in muscular power, explosiveness and RFD often occur without significant morphological increases of the trained muscle (i.e. no significant increases in muscle hypertrophy) (Ellenbecker, Davies, & Bleacher, 2012; Loturco et al., 2016).

Surprisingly, Bružas et al. (2016) documented a 4-week RT programme consisting of plyometric exercises with added external loads did not improve punching power or speed. It is likely that the research of Bružas et al. (2016) failed to observe improvements in punching performance due to the upper-body plyometric exercises being performed with added external loads. Previous research has highlighted how the addition of external load during plyometric exercises reduces movement speed and RFD in the upper-body (Hinshaw, Stephenson, Sha, & Dai, 2018), but enhances vertical and horizontal-jump performances significantly in the lower-body (Kange, 2018; Khlifa et al., 2010). Consequently, upper-body plyometric exercises implemented within a training programme designed to enhance movement velocity should do so with a load similar to that of the sporting action itself to replicate the actual speed of athletic performance (Brewer, 2017; McBride et al., 1999). Meanwhile, lower-body plyometrics may be performed with external loads equating to ~10% of body mass to increase the ability of lower-limb musculature to store and utilise elastic energy (Kang, 2018; Khlifa et al., 2010). Cheraghi et al. (2014) suggests plyometrics (non-weighted) should play a central role within a boxing-specific RT programme to augment SSC muscle functions and contractile RFD after observing the application of the SSC during rear-hand cross punches. Loturco et al. (2016) substantiates this suggestion by stating how PT should strive to augment ‘fighting-specific neuro-mechanical capacities’ (p.114) in boxers due to the ability of this training method to stimulate positive adaptations relating to the SSC and muscular recruitment. Additional authors also propose that PT provides an effective stimulus for enhancing punching power among combat athletes (Komi, 2003; Turner et al., 2011; Verkhoshansky et al., 1991; Wilson et al., 1993).

2.7.1.5. Contrast training

Within the current body of literature, it has been suggested utilising maximal strength and ballistic/plyometric exercises in the same training session can optimise strength and power performance greater than performing either training method alone (de Villarreal, Requena, Izquierdo, & Gonzalez-Badillo, 2013; Mangine et al., 2008; Rippetoe & Kilgore, 2009). This method of RT is commonly referred to as either 'contrast' or 'complex' training, although these terms are wrongly used interchangeably as distinct differences exist between the two methods. Contrast training (CT) involves alternating heavy and light RT loads on a set-for-set basis, whilst complex training involves performing all heavy load exercise sets first before completing the lighter load exercises after (Duthie, Young & Aitken, 2002; Jones, Bampouras, & Comfort, 2013). An example of CT would involve alternated maximal strength (e.g. bench press) and ballistic (e.g. bench throw) or plyometric (e.g. countermovement medicine ball chest throw) exercises for a specific number of sets (i.e. bench press; bench throw; bench press; bench throw). Meanwhile, an example of complex training would comprise a maximal strength exercise completed prior to a ballistic or plyometric exercise (e.g. bench press; bench press; bench throw; bench throw). CT protocols have been shown to augment muscular strength and muscular power greater than strength or power exercises performed in isolation (de Villarreal et al., 2013; Esformes, Cameron, & Bampouras, 2010; Rahmi & Behpur, 2005). Hammami, Negra, Shephard, and Chelly (2017) observed greater improvements across acceleration (5 m sprint), speed (40 m sprint), power (CMJ; squat jump) and agility (repeated change of direction ability) assessments among soccer players following a CT intervention compared to standard ST. de Villarreal et al. (2013) also documented greater increases in strength and power performance variables (back squat 1RM; 30-metre sprint; concentric squat-velocity) following CT compared to other RT methods (ST, OL, BT, and PT respectively).

The enhancement of muscular strength, muscular power and performance variables associated with these physical traits are suggested to occur as a result of CT taking advantage of a physiological event known as post-activation potentiation (PAP) (Jones et al., 2013). PAP is classified as a ‘phenomenon’ whereby a strong muscular contraction (usually resulting from ST using loads >87% 1RM) augments subsequent force-generation capabilities via elevated neural stimulation, enhanced motor-unit recruitment and myosin light-chain phosphorylation (Chiu & Barnes, 2003; Farup & Sørensen, 2010; Gilbert & Lees, 2005; Hrysomallis & Kidgell, 2001). As a result, CT can enhance force potential due to superior motor-unit availability in subsequent muscular contractions (Crewther et al., 2011), making this method of RT potentially useful to boxing where RFD is critical to success (Aagaard et al., 2002; Olsen & Hopkins, 2003; Loturco et al., 2016). This is reinforced within the paper of Cheraghi et al. (2014) whereby the authors recommend the use of CT to enhance punching velocity in elite amateur boxers. Thus, investigating the influence of CT on biomechanical and physical performance-related characteristics associated with maximal punching performance is warranted.

2.7.2. The influence of resistance training on punching performance

2.7.2.1. Common resistance training misconceptions and myths

Until recently, boxing at both amateur and professional levels was a sport reluctant to implement RT methods (Del Vecchio, 2011). Despite advancements in sports science, boxers and their coaches would often (and arguably still do) dismiss the established performance benefits observed in other sports associated with RT in favour of time-honoured methods (Price, 2006). Bourne et al., (2002) state how traditionally, boxers would prepare for a contest by completing various bodyweight/callisthenic exercises and long distance running alongside skill training encompassing pad work, sparring and punch bag intervals (Turner, 2009a). The hesitancy of boxing coaches and combatants to introduce RT into training programmes appears to lie in fears concerning increased body mass, decreased flexibility and aerobic capacity, reduced punching speed/velocity and excessive muscle mass (Del Vecchio, 2011; Ebben & Blackhard, 1997). Furthermore, the omission of RT in favour of excessive aerobic-based training was deemed the superior strategy for not only preventing diminished competitive performance, but also for ‘making weight’ as boxers and other combat sport athletes will often attempt to compete at their lowest possible weight to box against opponents of a lower body mass (Turner, 2009a).

However, RT can have a negative influence on boxing performance by impairing speed-strength, technical intricacies of punching and increasing muscle bulk if performed excessively with incorrect loading parameters (Verkhoshansky, 1986). Still, if implemented correctly within a boxer’s training programme, resistance exercises can enhance the impact force (Loturco et al., 2016), power (Čepulėnas et al., 2011; Del Vecchio et al., 2019; Hlavačka, 2014), acceleration (Loturco et al., 2014), and velocity (Markovic et al., 2016) of punches without significantly increasing body mass. Implementing a RT programme correctly within an amateur boxer’s training regimen can enhance performance and decrease injury potential through strengthening the muscular system, strengthening tendons and ligaments, augmenting the structural integrity of all involved joints and improving a boxer’s ability to produce explosive strength (Cordes, 1991; Turner et al., 2011). Indeed, much research has established the important role of RT in injury prevention across a range of sports, including those involving combat (James, 2014; Turner, 2009b; Wallace & Flanagan, 1999) Furthermore, a RT programme emphasising enhancements in maximal strength and power is unlikely to cause considerable increases in muscle bulk that have a detrimental effect on performance as force production is not principally a function of muscle size, but rather efficient neuromuscular stimulation (Verkhoshansky & Siff, 2009). Although progress has been made within the sport over recent years, it is evident knowledge of how to optimally increase punching performance through RT is still in its infancy (Turner et al., 2011).

2.7.2.2. How can resistance training enhance punch performance?

It has been noted that maximal strength and power often distinguish superior competitors within combat sports (James et al., 2017). Past research has also discovered the existence of a relationship between force and power production that highlights how an athlete will be unable to obtain considerable levels of power without first demonstrating a certain level of muscular strength (Cormie et al., 2011b). Therefore, the introduction of boxing- and/or boxer-specific RT programmes appear worthwhile considering RT is a highly effective method of enhancing maximal muscular strength and maximal neuromuscular power (Cormie et al., 2011b; Kraemer & Mazzetti, 2003; Suchomel et al., 2016).

Within the present body of literature, there is strong evidence to suggest that RT programmes and protocols can enhance characteristics of punching performance (Čepulėnas et al., 2011; Del Vecchio et al., 2019; Hlavačka, 2014; Kim et al., 2018). Early research in the area utilised varying methods to determine if physical and punching performance among boxers could be improved via specific RT programmes.

Getke and Digtyarev (1989) documented how a ST programme increased explosive strength, force output and maximal strength, which was suggested to enhance punching power and speed (although these variables were not assessed pre- or post-intervention). Solovey (1983) examined the effects of various weighted exercises (medicine balls and dumbbells) on punching velocity in young Soviet boxers, concluding that the use of RT enhanced the 'speed' (total time, time of the latent period and fist movement time) of single maximal punches significantly. Similar findings were also reported by Dengel et al. (1987) who found punch velocity improvements of 26% and 32% for the left and right hands, respectively, across the U.S. Olympic boxing team following a 2-week RT programme.

More contemporary research has reported the positive influence RT can have on punching performance. Markovic et al. (2016) documented 6-11% fist velocity improvements after 6-weeks of resistance band training. Meanwhile, Čepulėnas et al. (2011) documented impact force improvements of up to 44% (lead hand) and 17% (rear hand) among elite Lithuanian boxers following a 4-week intervention comprising 40% boxing training and 60% boxing-specific RT. For impact power, increases of 25-51% (Del Vecchio et al., 2017), 21.4% (Del Vecchio et al., 2019), ~6% (Hlavačka, 2014), and ~27% (Kim et al., 2018) in straight and hook punches have been reported at the conclusion of six-week, nine-week, and sixteen-week programmes, respectively. It is suggested these punch performance increases relate to the relationships between punch impact kinetics and muscular strength and power (r = 0.67-0.85) Loturco et al., 2016)), though further research is required to substantiate this claim.

Furthermore, Loturco et al. (2018) found mean and peak muscular power improvements in bench throw (+8%) and jump squat (+7%) performance among boxers following a 7-week intervention, concluding that characteristics of punching performance were also augmented based upon the relationship between punch impact forces and muscular power variables observed previously (Loturco et al., 2016). These results highlight the positive effects of a correctly implemented RT programme on punching performance.

More specifically, CT has been suggested to be highly beneficial to boxers striving to enhance punching performance. Matthews and Comfort (2008) posited that performing loaded movements that are biomechanically similar to punching (such as straight, hook, and uppercut punches on a cable-pulley machine) can have a potentiation effect on subsequent unloaded punches, augmenting the speed and power of the strike. Despite this suggestion appearing sound in theory, RT should replicate movements similar to those observed within the athlete’s sport (Cormie et al., 2011), but not be identical as performing complex sporting movements with external loads (such as punching with dumbbells and/or a cable-pulley machine) can have a negative influence on the technical intricacies, fine movement patterns and timing of punching, in addition to creating excessive load on the deltoid musculature and lumbar spine (Klatten, 2016). Strength and power performance increases are likely enhanced optimally through the use of traditional strength exercises as opposed to high-load sport-specific movements given the recommendations of Turner et al. (2011), Lenetsky et al. (2013), and Loturco et al. (2016). Consequently, coaches and boxers should look to implement resistance exercises that train specific movement patterns observed within boxing (i.e. shoulder protraction; elbow extension; trunk rotation; triple extension of the hip, knee and ankle), as opposed to adding external load to actual sport-specific techniques.

With the effects of RT on boxing performance acknowledged within certain studies, some authors have suggested performance can be augmented through the use of particular exercises that replicate specific movement patterns observed within boxing. Fitzmaurice (1982) and Estwanik (1991) suggested the inclusion of tricep dip and bench press exercises would improve the force and power of a boxer's punch via strengthening elbow extension. Lockwood and Tant (1997) meanwhile recommended the inclusion of weighted 'heel training' (plantar flexion) following EMG assessments of boxers. Furthermore, Spaniol (2012) and Turner et al. (2011) recommended the use of rotational medicine ball throws and triple extension exercises (e.g. squats, jump variations, Olympic lifts) to improve a boxer's ability to generate force throughout the kinetic chain. Such resistance exercises are supported by Filimonov et al. (1985) who observed how rear leg drive (38.46%), trunk rotation (37.42%) and elbow extension (24.12%) accounted for the total amount of force generated during straight punches among experienced Soviet boxers, each of which can be augmented through RT exercises (Fitzmaurice, 1982; Lockwood & Tant; 1997; Spaniol, 2012; Turner et al., 2011). Although an optimal RT programme would aim to include a specific exercise to enhance each movement pattern determined to be crucial to punching force, enhancing lower-body strength and power is essential. Punching force is paramount to successful boxing performance and cannot be optimised without taking advantage of the force potential of the lower-body (Smith & Draper, 2006), therefore, specificity of ST for boxers looking to enhance punching performance should focus on the lower body (Cheraghi et al., 2014).

Previous research (McGill et al., 2010) has highlighted how elite striking performance involves a contraction-relaxation-contraction cycle of the trunk musculature. This suggests it may be beneficial to perform RT exercises that emphasise a rapid rate of relaxation coupled with a rapid rate of contraction to enhance the trunk's ability to transfer force. This can be achieved through the inclusion of ballistic rotational throwing exercises that generates considerable force at the trunk following a brief period of relaxation which is subsequently transferred distally to the upper extremities via sequential kinetic linking (Spaniol, 2012). It may also be useful for boxers to include RT exercises that increase the speed/velocity of the upper extremities as this has been suggested to be a key determinant of punching impulse and impact-force (Mack et al., 2010; Nakano et al., 2014). Whilst this suggests the inclusion of primarily upper-body exercises to achieve improvements in punching performance are necessary, Lenetsky et al. (2013) convey how hand velocity is predominantly influenced by leg drive through the transmission of forces along the kinetic chain. Therefore, whilst upper-body exercises are advantageous to boxers, lower-body exercises involving triple extension appear superior for optimising punching performance.

Additional findings of interest can be extrapolated from research into baseball pitching which discovered how weakness in knee and hip joints can negatively affect the transfer of force within the kinetic chain (Burkhart, Morgan, & Kibler, 2003; Kageyama et al., 2014). Due to the kinetic and kinematic similarities between the techniques of punching and pitching, strengthening the knee and hip joints via RT would appear to improve a boxer's ability to transfer force across the kinetic chain whilst also minimising injury risk. This has also been noted among elite shot putters whereby virtually half of their throwing/putting performance is derived from the triple extension of the lower body (ankle, knee and hip joints) (Terzis et al., 2003). Whilst leg drive is arguably the principal component relating to optimal punching performance (Cheraghi et al., 2014; Lenetsky et al., 2013; Turner et al., 2011), the hip and pelvis also contribute significantly to the impact force of a punch by permitting the lower-body to put a considerable quantity of force through the ground, which in turn, promotes substantial internal rotation and triple extension of the hip joint (Arus, 2013; Ralston, 1999). These statements further support the inclusion of RT exercises that emphasise extension of the ankle, knee and hip joints (triple extension) to enhance punching performance among amateur boxers.

Despite previous research highlighting the positive influence RT can have upon boxing, it is still unclear as to which RT method is optimal at enhancing punching performance. Whilst some research has shown how CT enhanced various strength and power performance variables more than ST, OL, BT, and PT (de Villarreal et al., 2013), it is still unknown if CT is superior to other RT methods for improving punching performance alongside physical and physiological characteristics.

2.8. Conclusion

This review has highlighted the limited body of knowledge relating to the biomechanics and physiology of punches and the influence of RT on punching performance. It is clear maximal punching has not been investigated comprehensively, with researchers often focussing on a single punch technique (usually the rear-hand cross). Certain punch types, such as the lead and rear uppercuts, have been virtually ignored despite their important potential during a contest. In terms of training, it is apparent there is a need for the creation of a detailed resistance exercise programme catered towards optimising maximal punching performance. The relative lack of research in general reflects the long-standing reluctance of boxing as a sport to adopt the practices observed within contemporary sports science. It would be beneficial for boxers and coaches to be made aware of the factors influencing punching in order that they might adopt training practices more suited to enhancing punching performance, and overall competition outcomes.

While some researchers have determined muscular strength and power developed along the sagittal plane (i.e. via back squat, bench press) are associated with punching impact forces (Loturco et al., 2016), other physical performance-related attributes such as speed and muscular power along the frontal and transverse planes have not been examined. Additionally, the need for acquiring both kinetic and kinematic data during different punching techniques is essential in order to establish the biomechanical characteristics of each punch type and how these characteristics can be developed within training. The kinematic differences between punch types (i.e. straights, hooks and uppercuts) remain uncertain, as are the kinetics of each punch technique, particularly GRF.

It has been established that a powerful punch is initiated via the recruitment of lower-body musculature which acts as a conduit for force to travel distally through the body to the point of impact made by the fist (Cheraghi et al., 2014; Dyson et al., 2007; Filimonov et al., 1985; Lenetsky et al., 2013; Turner et al., 2011). Previous research has established a strong association between strength and power qualities and punching ability among amateur boxers (Chaabene et al., 2015; Loturco et al., 2016; Obmiński et al., 2011), although the interaction between punching performance and physical attributes such as speed, acceleration and rotational power have not been reported. This is surprising considering the importance of these attributes to boxing performance (Chang et al., 2011; Loturco et al., 2014; Spaniol, 2012). Moreover, given the certain impact on such qualities afforded by specific RT, it would seem worthwhile that the effectiveness of different contemporary RT interventions (such as BT, PT, ST, and CT) on punching performance is examined.

Chapter 3

An analysis of the three-dimensional kinetics and kinematics of maximal effort punches among amateur boxers

The contents of this chapter form the basis of the following publication:

Stanley, E., Thomson, E., Smith, G., & Lamb, K.L. (2018). An analysis of the three-dimensional kinetics and kinematics of maximal effort punches among amateur boxers. *International Journal of Performance Analysis in Sport, 18*(5), 835-854.

Abstract

The purpose of this study was to quantify the three-dimensional kinetics and kinematics of different punch types (jab, rear-hand cross, lead and rear hook, lead and rear uppercut) among amateur boxers. Fifteen male boxers (age: 24.9 ± 4.2 years, stature: 178 ± 8.0 cm; body mass: 75.3 ± 13.4 kg; years of experience: 6.3 ± 2.8 years) performed maximal effort punches against a suspended punch bag during which upper-body kinematics were assessed using a 3D motion capture system and ground reaction force (GRF) of the lead and rear legs were recorded via two force plates. Peak fist velocity, punch delivery time, peak shoulder and elbow joint angular velocities were quantified for each punch type. For all variables except elbow joint angular velocity, analysis revealed significant ($P < 0.05$) differences between straight, hook and uppercut punches. The lead hook exhibited the greatest peak fist velocity (11.95 ± 1.84 m/s), the jab the shortest delivery time (405 ± 0.15 ms), the rear uppercut the greatest shoulder joint angular velocity (1069.81 ± 104.5 deg/s), and the lead uppercut the greatest elbow angular velocity (650.96 ± 357.5 deg/s). Proximal to distal sequencing of the timings of peak angular velocities was only apparent in jab and rear-hand cross punches. Lead leg net braking and rear leg net propulsive impulses were greatest for the rear hook, while lead and rear leg vertical impulses were highest for the lead hook, respectively. Peak resultant GRF different significantly ($P < 0.001$) between rear and lead legs for the jab punch only. Vertical GRF accounted for a larger degree of total GRF than anteroposterior or mediolateral GRF for both lead and rear legs across all punch types. Peak lead hook fist velocity was moderately correlated with peak lead leg GRF, and peak shoulder and elbow joint angular velocities, respectively. Hooks and uppercuts had longer delivery times than straight punches, yet reached higher end-point fist velocities. Whilst these findings provide novel descriptive data for coaches and boxers, future research should examine if physical and physiological capabilities relate to the key biomechanical qualities associated with maximal punching performance.

Key words: combat sports, boxing, punching, technique analysis.

3.1. Introduction

Boxing punches are intricate actions requiring the recruitment of leg, trunk and arm musculature to function synergistically in a coordinated manner (Turner et al., 2011). Despite the importance of punching to successful performance, there is only a limited amount of biomechanical knowledge for most of its techniques. Some kinematic characteristics (such as joint angles and velocities and punch velocity) have been investigated for certain punches (jabs, rear-hand crosses, lead hooks, rear hooks and rear uppercuts: Cabral et al., 2010; Cheraghi et al., 2014; Kimm & Thiel, 2015; Piorkowski et al., 2011) among competitive boxers. For example, research has reported the delivery times and fist velocities of straight (357 ± 178 ms and 5.9 m/s - 8.22 m/s) and hook (477 ± 203 ms and 8 m/s - 11 m/s) punches, respectively (Cheraghi et al., 2014; Piorkowski et al., 2011), though from a biomechanical perspective, further analysis remains warranted.

Joint and punch velocities are dependent upon a proximal-to-distal sequencing pattern initiated by the lower limbs that travels distally through the pelvis, trunk and arm before peaking at the fist, causing the acceleration of the fist towards the target (Cheraghi et al., 2014). Proximal-to-distal sequencing and the subsequent velocities generated via rapid joint rotations have been observed in various punching and kicking techniques across combat sports (Estevan et al., 2015; Sorensen et al., 1996; VencesBrito et al., 2011). Fist velocity has also been suggested to be dependent upon the distance of the acceleration path to the target, with hook punches exhibiting greater values than straight punches due to a longer acceleration pathway that facilitates the generation of greater pre-impact fist velocities (Piorkowski et al., 2011; Viano et al., 2005; Whiting et al., 1988). However, how joint and fist velocity differ between straight, hooks, and uppercuts has not been reported within the scientific literature.

Kinetic characteristics have also been shown to influence properties of punching, particularly ground reaction forces (GRF) (Mack et al., 2010; Yan-ju et al., 2013). For example, the force generated by the rear leg has been suggested to contribute considerably to the performance of rear hand punches (Cheraghi et al., 2014; Filimonov et al., 1985; Turner et al., 2011), whilst Yan-ju et al. (2013) noted lead leg force was a significant contributor to jab fist velocity. However, Mack et al. (2010) reported only small, albeit significant, relationships between lower body forces and peak hand velocity for rear hook (R^2 = 0.103) and rear-hand cross (R^2 = 0.099) punches, respectively, suggesting further research is warranted here. Moreover, whilst their relevance has been alluded to (Lenetsky et al, 2013), no scientific studies have examined the direction (anteroposterior, mediolateral, vertical) of GRF during specific punch types.

With the general lack of empirical evidence, coaches and boxers are unlikely to have the means to form an understanding of how punches can be enhanced through kinetic and kinematic assessments and how knowledge and information quantified via such assessments can influence performance. In the manner of previous appraisals of sports techniques (Kageyama, Sugiyama, Takai, Kanehisa, & Maeda, 2014; Torres, 2013; Wagner et al., 2014), gathering information relating to fist velocity, GRF production and their relationship across different punch techniques could facilitate a grasp of the technical characteristics of different punch techniques and lead to the development of punch-specific training interventions.

The overall aim of this study therefore was to quantify the GRF and kinematic characteristics of a variety of maximal punches among amateur boxers. The main objectives were to: (i) assess peak fist velocities and delivery times across punch types; (ii) examine the differences in lead and rear leg resultant GRF and its directional application across punch types; (iii) quantify lead leg net braking, rear leg net propulsive and lead and rear leg vertical impulse across punch types, and (iv) quantify the relationships between kinematic (punch delivery time, peak shoulder joint resultant angular velocity, peak elbow joint resultant angular velocity) and kinetic (peak lead and rear leg resultant GRF, lead leg net braking and vertical impulse, rear leg net propulsive and vertical impulse) variables and peak resultant fist velocity.

3.2. Methods

3.2.1. Participants

Fifteen males (age: 24.9 ± 4.2 years; stature: 177.9 ± 8.0 cm; body mass: 75.3 ± 13.4 kg; years of experience: 6.3 ± 2.8 years) across seven weight categories (flyweight (49-52 kg) to super-heavyweight (91+ kg)) were recruited from six amateur boxing clubs located across the North West of England, based upon current boxing experience (≥ 2 years) and official bout history (≥ 2 bouts). A sample size calculation (G*Power version 3.1.9.4, Universität Düsseldorf, Dusseldorf, Germany - Faul et al., 2009) based on standard input parameters (α level = 0.05, power = 0.8) and effect sizes (0.68 for punch delivery time and 0.99 for contact speed) gleaned from Piorkowski et al. (2011), yielded a sample of 12 (see Appendix 1). All participants provided written informed consent prior to the study and institutional ethical approval was granted by the Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee (see Appendix 12).

3.2.2. Design

The study adopted a within-subjects design to assess kinetic and kinematic aspects of six maximal punches (jab, rear-hand cross, lead and rear hook, lead and rear uppercut) considered to represent the principal techniques observed in boxing competition (El Ashker, 2011; Kapo et al., 2008; Thomson & Lamb, 2016). All data were collected in one session and participants did not require a separate familiarisation trial as all had experience (≥ 2 years) performing the punch techniques and were familiar with punching a target similar to that used in the present study. Twelve kinematic and fourteen kinetic variables were measured with respect to the six punch types via a 3D motion capture system and two embedded force platforms, respectively.

3.2.3. Procedures

For all punch trials, a water-filled punch bag that resembled the average height of a human head (9 in) (Aqua Bag 'Headhunter' model, Aqua Training Bag, New York, United States) was used to provide a striking target (Figure 3.1). Utilising a punch target that moves upon impact has been advocated (Atha et al., 1985; Nakano, Lino, Imura, & Kojima, 2014; Tong-Iam et al., 2017) as an effective way of ensuring maximal effort punches. The punch bag was suspended at the shoulder level of each participant by a heavy-duty steel chain secured by a punch bag hook located above the designated testing area. Three reflective markers were placed on the top of the punch bag in order to permit the 3D cameras to detect its movement upon impact. This movement acted to verify the instance of punch contact (Figure 3.2).

Figure 3.1. Aqua Bag 'Headhunter' punch target.

Seventy six reflective markers were placed on specific anatomical landmarks of each participant to facilitate a comprehensive assessment of full-body kinematics in 3D spaces across six degrees of freedom (Figure 3.3) (body segments defined by Vanrenterghem, Gormley, Robinson, & Lees, 2010). Of the 76 markers, 16 were utilised for calibration purposes only and were removed during the dynamic trials. The head was not required for analysis, while the hand segments (Figure 3.4) were defined as per Piorkowski et al. (2011) (to obtain detailed fist velocity data). These segments included the upper arm (left and right), lower arm (left and right), thorax, pelvis, upper leg (left and right), lower leg (left and right), and foot (left and right). Markers allocated to the 'radial wrist', 'ulnar wrist' and 'glove centre' defined the hand segment (Figure 3.4).

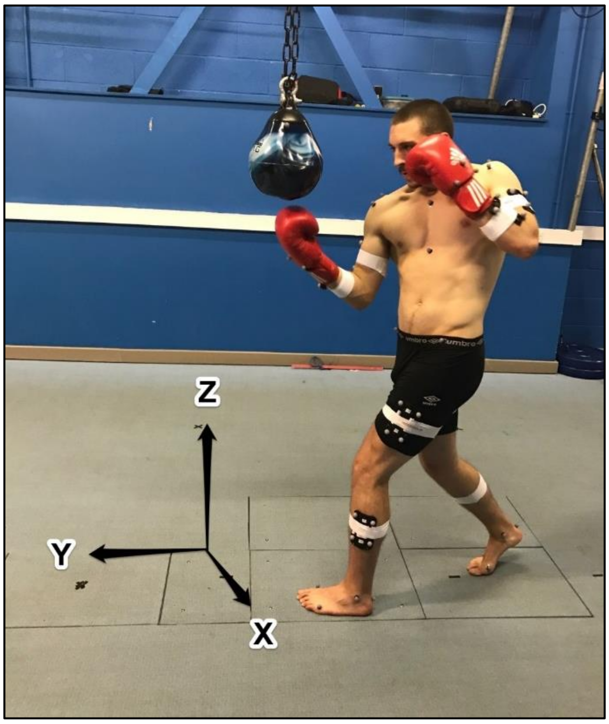

Figure 3.2. Laboratory coordinate system and punch target.

Following calibration, the 3D positions of all reflective markers were obtained from eight opto-electronic ceiling mounted cameras (Oqus 7+ system, Qualisys Inc., Gothenburg, Sweden). Kinematic data was obtained via Qualisys Track Manager (QTM) (Version 2.14, Qualisys Inc., Gothenburg, Sweden), sampled at 300 Hz, and analysed using Visual 3D (Version 6, C-Motion Inc., Rockville, United States). GRF data were collected from both the lead and rear legs of each participant for all punch trials by two embedded force platforms (model 9281CA with 600 x 400 mm internal amplifiers, Kistler Instruments, Hampshire, UK), and sampled at a rate of 900 Hz.

Prior to testing, participants completed a 10-min self-selected warm-up comprising generic and boxing-specific activities such as jogging, dynamic stretches and shadow-boxing (Smith et al., 2000). The boxers were permitted to strike the punch bag whilst wearing the reflective markers until they became familiarised with the set up and positioning of the target (~5 min).

All were instructed to strike the punch bag using a single, maximum effort punch (termed as a knock-out punch) whilst maintaining the correct technique for the specific punch type performed. Boxers wore fabric hand-wraps (450 cm length, 5 cm width; Adidas, Germany) and boxing gloves (284 g; Adidas, Germany) as required during competition.

Six punch types (jab, rear-hand cross, lead hook, rear hook, lead uppercut, rear uppercut) were performed from either an orthodox (left foot leading) or southpaw (right foot leading) stance (Hickey, 2006), depending on the preference of each participant (orthodox n = 11; southpaw n = 4). Previous research (Bingul, Bulgan, Tore, Bal, & Aydin, 2018) has reported comparable punch impact forces between orthodox (1501 ± 316 N) and southpaw (1462 ± 371 N) boxers, in addition to impact accelerations (orthodox - 30.76 ± 6.5 m/s^2, southpaw – 29.96 ± 7.6 m/s^2) and fist velocities (orthodox - 10.58 ± 1.3 m/s, southpaw – 10.61 ± 1.4 m/s), respectively, for hook punches. Therefore, it is deemed that boxing stance will not have a significant influence on maximal punch kinetic and kinematic data.

Each punch was performed five times in succession with 60 s recovery period between trials. In the manner of previous related research, all punches were performed in the order of (1) jab; (2) rear-hand cross; (3) lead hook; (4) rear hook; (5) lead uppercut and; (6) rear uppercut. This was to standardise the testing procedure across all participants and promote the precision/accuracy of each trial (i.e. boxers strike the same area of the target) (Lenetsky et al., 2017; Piorkowski, 2009). Furthermore, with 30 punches to complete, it was important to reduce the effects of fatigue upon data collection. Though ample rest was provided between efforts, it was also felt the execution of the most efficient (Hickey, 2006) and least energetically demanding punches (i.e. straight punches) (El Ashker, 2011) before progressing to the more demanding hook and uppercut punches (Kapo et al., 2008) was an effective strategy to manage fatigue and ensure technique was not hampered at any point during testing. Moreover, the order of punches followed the percentage of specific punches executed in competition, with the most frequently observed punch (i.e. jab) performed first and the least observed (i.e. uppercuts) performed last (Davis et al., 2013; 2015; 2017; 2018; El Ashker, 2011; Kapo et al., 2008; Thomson & Lamb, 2016). Performance feedback was not provided during the testing procedures.

3.2.4. Data processing

Kinematic and GRF data was analysed via Qualisys Track Manager (QTM) (version 2.14, Qualisys Inc., Gothenburg, Sweden), whereby reflective markers and anatomical landmarks were labelled. Thereafter, punch trials were exported to Visual 3D (Version 6, C-Motion Inc., Rockville, United States) from which full-body joint segments and key events were created alongside the calculation of kinematic and GRF data.

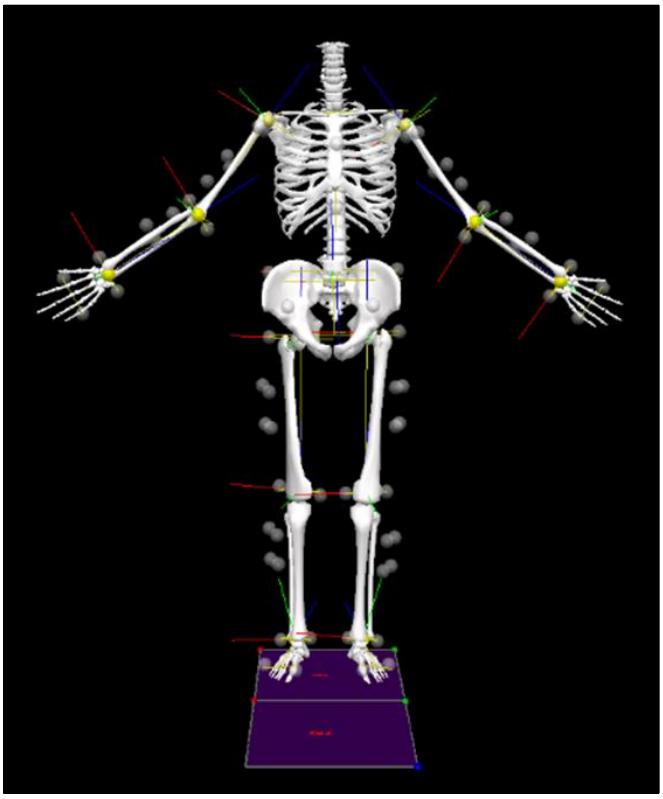

Figure 3.3. Local coordinate system of the adapted marker model.

Figure 3.4. Upper-extremity marker set (adapted from Piorkowski et al., 2011; Vanrenterghem et al., 2010).

Key events (see below) were identified from visual observations due to the differing technical intricacies and punch set-ups across each individual participant (e.g. a hook punch performed directly from the guard versus a hook punch thrown from a ‘bobbing and weaving’ motion). These events were classified as: (i) INITIATION (the initiation of a countermovement prior to the fist being projected towards the punch target), identified from the descent of the hand segment markers on the punching hand along the longitudinal axis (Figure 3.5); and (ii) CONTACT (one frame prior to the fist impacting the punch target), identified from the initial movement of the markers located on the punch target (Figure 3.6). These event labels were subsequently used to export kinematic and GRF data in ASCII formats to be further analysed in Microsoft Excel (Microsoft Corporation, Reading, UK).

The kinematic variables computed from the punch data were: punch delivery time from event markers INITIATION to CONTACT (ms), peak resultant fist velocity of the hand segment (defined from ‘radial wrist’, ‘ulnar wrist’, ‘knuckle 1’, and ‘knuckle 5’ tracking markers) from INITIATION to CONTACT (m/s), peak resultant shoulder joint angular vector velocity (shoulder joint defined from upper arm tracking markers relative to the defined thorax/ab segment) from INITIATION to CONTACT (deg/s), peak resultant elbow joint angular vector velocity (elbow joint defined from the upper arm and forearm tracking markers) from INITIATION to CONTACT (deg/s), peak flexion-extension lead and rear hip joint angles (hip joint defined from thigh tracking markers relative to the pelvis) from INITIATION to CONTACT (deg), peak flexion-extension lead and rear knee joint angles (knee joint defined from thigh and shank cluster markers) from INITIATION to CONTACT (deg), peak flexion-extension lead and rear ankle joint angles (ankle joint defined from ‘heel’, ‘lateral ankle’, ‘medial ankle’, ‘toe 1’ and ‘toe 5’ tracking markers) from INITIATION to CONTACT (deg), peak flexion-extension lead and rear hip joint angular vector velocities from INITIATION to CONTACT (deg/s), peak flexion-extension lead and rear knee joint angular vector velocities from INITIATION to CONTACT (deg/s), and peak flexion-extension lead and rear ankle joint angular vector velocities from INITIATION to CONTACT (deg/s).

Peak joint velocity timings (% movement) were quantified from the timing of peak angular joint velocity (shoulder and elbow) from punch data normalised to 101 data points. All marker data were sampled at a rate of 300 Hz and filtered using a low-pass Butterworth filter with a cut-off frequency of 12 Hz (see Appendix 2) prior to and after the computer link-model based data had been generated to reduce the potential noise in the signal (as suggested in previous boxing-related research; Piorkowski et al., 2011). This cut-off frequency was deemed appropriate following pilot work whereby data were visually inspected for unwanted signal noise. The same data processing methods were implemented across the data-set, meaning any potential errors were consistent.

The kinetic variables computed from the punch data were: peak lead leg resultant GRF, peak rear leg resultant GRF, total lead leg net braking impulse, lead leg vertical impulse, total rear leg net propulsive impulse, total rear leg vertical impulse, peak lead hip joint flexor-extensor moment, peak rear hip joint flexor-extensor moment, peak lead knee joint flexor-extensor moment, peak rear knee joint flexor-extensor moment, peak lead ankle joint flexor-extensor moment and peak rear ankle joint flexor-extensor moment (all from INITIATION to CONTACT). Peak GRF timings (% movement) were quantified from the timing of peak lead and rear leg GRF from punch data normalised to 101 data points. GRF data were sampled at 900 Hz and low-pass filtered using a 4th-order Butterworth filter with a cut-off frequency of 100 Hz selected based on recommendations in previous research for baseball pitching (1000 Hz sampling rate, 20 Hz cut-off frequency - Huang & Lin, 2011), discus throwing (1000 Hz sampling rate - Yu, Broker, & Silvester, 2002), overarm throwing (960 Hz sampling rate, 40 Hz cut-off frequency - Ramsey, Crotin, & White, 2014), and punching (1000 Hz sampling rate, 100 Hz cut-off frequency - Lenetsky et al., 2019) across all assessed variables. In addition, a period of pilot work was also completed whereby data was visually inspected for discrepancies (i.e. unwanted noise, over-smoothing) to ensure the applied cut-off frequency was high as possible to acquire accurate joint kinetic and kinematic data whilst minimising potential errors (Bezodis, Salo, & Trewartha, 2011). A range of sample rates (500-3000 Hz) and cut-off frequencies (20-1000 Hz) were analysed using data gathered during pilot work, with the chosen sampling rate (900 Hz) and cut-off frequency (100 Hz) deemed the most suitable. Though the selected processing techniques were considered to be adequate for the current study, it is acknowledged that a different cut-off frequency or filter variation could have been employed that may have produced more accurate data values. Similarly to the kinematic variables, the same data processing methods were implemented across the data-set, meaning any potential errors were consistent across the entire dataset. Peak joint moments were filtered at 12 Hz based upon previous research analysing dynamic/ballistic full-body tasks (Dai, Mao, Garrett, & Bing, 2015; Farana et al., 2014; Fleisig, Barrentine, Zheng, Escamilla, & Andrews, 1999; Peng, Huang, & Kernozek, 2007; Williams, 2012; Yu & Andrews, 1998). Lead leg net braking impulse (negative Fy), rear leg net propulsive impulse (positive Fy) and vertical impulse (Fz) of both legs were calculated as the sum of frame-by-frame GRF x time from INITIATION to CONTACT. All GRF data (peaks, moments and impulses) were normalised to participant's body mass (N/kg).

3.2.5. INITIATION key event identification

The instant of INITIATION for each punch type was subject to test-retest intra-observer reliability testing. For each punch type, ten trials were randomly selected for analysis with the time between force plate contact (recorded objectively by the Kistler platforms) and punch initiation (determined by the lead researcher) recorded in Visual 3D.

Analysis revealed INITIATION identification was consistent across punch trials, with low typical error (Hopkins, 2000), low CV% (Roberts & Priest, 2006), and narrow limits of agreement (Bland & Altman, 1999) observed for each punch type (Table 3.1). Consequently, the reliability of punch INITIATION was deemed acceptable given the variation was unlikely to have had a meaningful impact upon the interpretation of the dependent variables (i.e. punches remained distinguishable from one another).

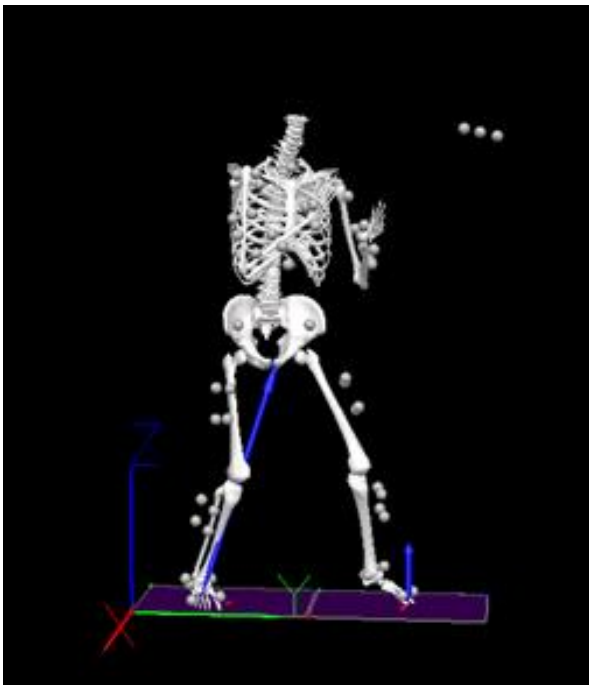

Figure 3.5. Rear uppercut INITIATION event.

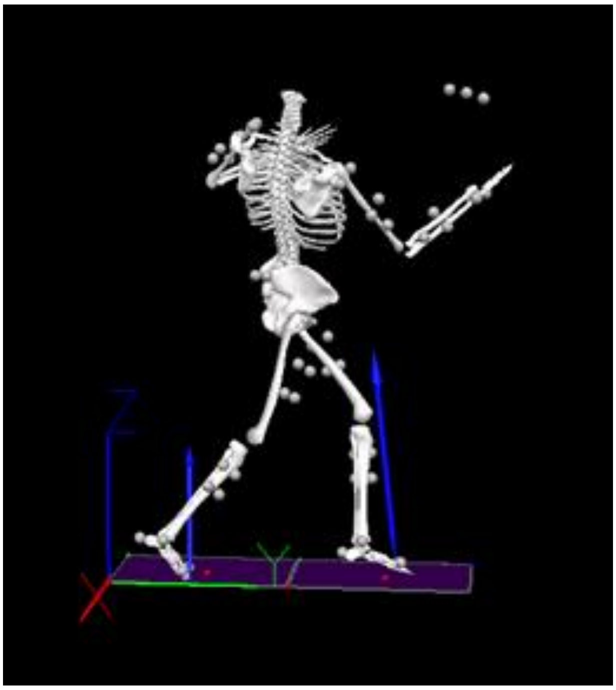

Figure 3.6. Rear uppercut CONTACT event.

Table 3.1. Reliability statistics for the identification of INITIATION (time between the instance of force plate contact to the point of punch initiation).

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
Random punch trial	**Test**	**Retest**	**Test**	**Retest**	**Test**	**Retest**	**Test**	**Retest**	**Test**	**Retest**	**Test**	**Retest**
1	0.25	0.23	1.27	1.29	0.59	0.57	1.27	1.29	2.17	2.17	0.19	0.15
2	3.30	3.33	1.27	1.28	0.62	0.65	1.27	1.28	1.82	1.8	0.72	0.68
3	0.32	0.27	1.91	1.93	3.13	3.15	1.91	1.93	1.97	1.98	0.51	0.49
4	0.25	0.27	0.04	0.05	0.59	0.59	0.04	0.05	1.23	1.23	0.35	0.33
5	2.98	2.99	0.38	0.38	0.10	0.08	0.38	0.38	1.19	1.18	0.60	0.61
6	0.11	0.11	0.49	0.5	1.02	1.00	0.49	0.5	2.69	2.67	1.48	1.47
7	1.84	1.79	0.43	0.42	2.53	2.52	0.43	0.42	1.29	1.3	1.83	1.85
8	1.65	1.65	1.62	1.61	0.46	0.43	1.62	1.61	0.56	0.57	1.74	1.72
9	0.27	0.27	0.02	0.04	0.10	0.11	0.35	0.34	0.03	0.05	1.69	1.63
10	1.86	1.84	0.77	0.74	0.31	0.33	0.77	0.74	0.19	0.20	0.01	0.01
M ± SD	1.28 ± 1.21	1.28 ± 1.22	0.82 ± 0.66	0.82 ± 0.66	0.95 ± 1.03	0.94 ± 1.04	0.85 ± 0.62	0.85 ± 0.63	1.31 ± 0.87	1.32 ± 0.86	0.81 ± 0.83	0.80 ± 0.82
TE (s)	0.01		0.01		0.01		0.01		0		0.01	
CV (%)	2.69		0.1		3.95		2.64		4.3		2.77	
95% LoA (s)	0.09± 0.05		0 ± 0.05		0 ± 0.04		0 ± 0.03		0 ± 0.02		0.01 ± 0.05	

M ± SD = mean ± standard deviation
S = seconds
TE (%) = Typical error
95% LoA = 95% limits of agreement

3.2.6. Statistical analysis

Descriptive statistics (mean ± SD) were generated for all dependent variables and their distributions checked for normality via Shapiro-Wilk tests utilising SPSS (version 23, Chicago, USA). As these conditions were met, a one-way repeated measures analysis of variance (ANOVA) was used to compare mean values across punch types with Bonferroni-adjusted *t*-tests adopted as a post-hoc procedure to identify where specific differences existed. Effect sizes were calculated as: $d = (\bar{x}1 - \bar{x}2)$ / SD; where $\bar{x}1$ and $\bar{x}2$ represent the two sample means and SD the pooled standard deviation. The magnitude of Cohen's *d* effect sizes were classified as: trivial < 0.2, small 0.2-0.6, moderate 0.6-1.2, large 1.2-2.0, and very large > 2.0 (Hopkins, 2004). Furthermore, the relationships between kinematic and GRF (lead and rear leg), impulse (lead and rear leg net braking, net propulsive and vertical), and peak resultant fist velocity were assessed via the Pearson product-moment coefficient (with 95% confidence intervals) and interpreted with the thresholds: < 0.1 (trivial); 0.1-0.3 (small); 0.3-0.5 (moderate); 0.5-0.7 (large); 0.7-0.9 (very large) and > 0.9 (nearly perfect) (Hopkins, 2002).

3.3. Results

3.3.1. Ankle, knee and hip joint angle

The effect of punch type was significant for both lead ($F_{(2.9, 39.8)} = 5.2$, $P = 0.004$) and rear peak flexion-extension ankle angles ($F_{(2.9, 49.5)} = 5.8$, $P = 0.002$). Post-hoc analysis revealed significant differences between all lead hand punches (jab, lead hook and lead uppercut) compared to all rear hand punches (rear-hand cross, rear hook and rear uppercut) for peak extension angle of the lead ankle (P = 0.001-0.018, ES = 1.4-1.7). Meanwhile, significant differences were also observed between the jab and all other punch types for the rear ankle (extension angle) (P = 0.001-0.018, ES = 1.2-1.6).

Punch type had a significant effect on peak lead knee flexion-extension joint angle ($F_{(3.0, 42.3)}$ = 5.8, P = 0.002), with significantly higher values evident in the all of the lead hand punches compared to all rear hand punches (P = 0.007-0.019, ES = 1.5-1.6). For peak rear knee flexion-extension joint angle, the effect of punch type was not significant ($F_{(3.4, 48.4)}$ = 2.4, P = 0.068).

A significant punch type effect was noted for peak lead hip flexion-extension angle ($F_{(2.3, 43.2)}$ = 20.4, P < 0.001), as it also was for peak rear hip flexion-extension angle ($F_{(2.2, 31.1)}$ = 32.7, P < 0.001). The lead hook had the greatest peak lead hip extension angle, being almost three times that of the rear-hand cross, rear hook and rear uppercut (ES = 1.6-1.8), respectively. Meanwhile, for the rear hip, the rear-hand cross exhibited the greatest peak extension angle, which was significantly greater than the jab, lead hook and lead uppercut (P < 0.001, ES = 1.8-2.0), but no other rear hand punches.

3.3.2. Ankle, knee and hip joint angular velocity

Peak lead ankle joint flexion-extension angular velocities were consistently lower than observed for the rear ankle, though both variables had a significant punch type effect ((lead ankle - $F_{(3.5, 49.7)}$ = 1.9, P = 0.008; rear ankle - ($F_{(3.6, 51.5)}$ = 9.0, P < 0.001)). The lead hook exhibited the greatest peak lead ankle joint extension velocity and was significantly larger than the jab and rear-hand cross (P = 0.004-0.046, ES = 1.0-1.2).

Meanwhile, the jab produced the largest peak extension angular velocity for the rear ankle compared to other punch types, though these differences were not significant (P = 0.073-0.166, ES = 0.3-0.8).

Peak lead knee joint flexion-extension angular velocity was significant according to punch type ($F_{(3.6,\ 51.2)}$ = 3.5, P = 0.015), as was peak rear knee joint flexion-extension angular velocity ($F_{(4.2,\ 59.2)}$ = 3.8, P = 0.006). The lead hook exhibited significantly greater peak lead knee extension angular velocities than the jab, rear-hand cross, rear hook and rear uppercut (P = 0.003-0.039, ES = 1.5-1.7), while the only significant punch difference observed for the rear knee (peak extension angular velocity) was between the jab and lead hook (P = 0.045, ES = 1.0).

Punch type had a significant effect on peak lead hip joint flexion-extension angular velocity ($F_{(2.8,\ 40.5)}$ = 16.1, P < 0.001), with significantly higher extension angles evidenced for the lead hook compared to the rear-hand cross, rear hook and rear uppercut, respectively (P < 0.000-0.047, ES = 0.9-1.2). Peak rear hip joint flexion-extension angular velocity was also significant different between punch types ($F_{(3.1,\ 44.0)}$ = 16.3, P < 0.001), with the rear uppercut exhibiting significantly higher peak extension angles than the lead hook and lead uppercut, respectively (P < 0.000-0.008, ES = 1.3-1.7).

Table 3.2a. Kinematic variable values of punch techniques.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Peak lead ankle joint angle (deg)	$72.8 \pm 6.1^{C, RH, LU}$	$50.1 \pm 7.0^{J, LH, LU}$	$77.1 \pm 4.2^{C, RH, LU}$	$48.3 \pm 7.0^{J, LH, LU}$	$76.6 \pm 9.7^{C, RH, LU}$	$54.7 \pm 4.9^{J, LH, LU}$
Peak rear ankle joint angle (deg)	$96.0 \pm 5.3^{C, LH, LU}$	94.9 ± 7.1^{J}	77.4 ± 7.7^{J}	90.3 ± 6.0	67.1 ± 7.4^{J}	91.7 ± 7.3
Peak lead ankle joint angular velocity (deg/s)	84.4 ± 25.9^{LU}	87.9 ± 25.6^{LU}	$121.5 \pm 30.5^{J, C}$	114.5 ± 28.6	113.3 ± 25.1	105.0 ± 33.0
Peak rear ankle joint angular velocity (deg/s)	154.6 ± 26.2	123.7 ± 30.7	146.8 ± 28.7	130.1 ± 23.7	131.7 ± 30.4	140.6 ± 34.9
Peak lead knee joint angle (deg)	$47.2 \pm 8.7^{C, RU}$	$28.6 \pm 10.4^{J, LH, LU}$	$50.3 \pm 9.8^{C, RU}$	$31.0 \pm 7.9^{J, LH, LU}$	$49.2 \pm 9.3^{C, RU}$	$28.5 \pm 8.6^{J, LH, LU}$
Peak rear knee joint angle (deg)	62.9 ± 6.6^{LU}	59.9 ± 11.4	50.1 ± 11.6	58.3 ± 9.1	48.7 ± 8.8^{J}	57.9 ± 7.4
Peak lead knee joint angular velocity (deg/s)	$158.0 \pm 37.8^{LH, LU}$	$146.9 \pm 39.4^{LH, LU}$	$244.5 \pm 28.8^{J, C, RH, RU}$	$154.9 \pm 42.9^{LH, LU}$	$217.3 \pm 39.6^{J, C, RH, RU}$	$173.0 \pm 38.7^{J, C, LH, RH}$
Peak rear knee joint angular velocity (deg/s)	263.8 ± 34.0^{LH}	255.7 ± 45.1	202.0 ± 32.4^{J}	239.5 ± 45.4	228.0 ± 41.7	245.2 ± 38.4
Peak lead hip joint angle (deg)	89.6 ± 8.9	42.0 ± 9.2^{LH}	$124.5 \pm 7.7^{C, RH, RU}$	46.2 ± 7.9^{LH}	118.7 ± 4.6	45.1 ± 7.4^{LH}
Peak rear hip joint angle (deg)	35.2 ± 8.2^{C}	$166.6 \pm 6.8^{J, LH, LU}$	58.5 ± 6.3^{C}	159.5 ± 7.5	42.1 ± 4.7^{C}	161.3 ± 7.0

Peak lead hip joint angular velocity (deg/s)	334.8 ± 74.3[C, RH, RU]	260.3 ± 130.7[J, LH, LU]	419.9 ± 91.0[C, RH, RU]	259.8 ± 104.0[J, LH, LU]	370.7 ± 94.1[C, RH, RU]	260.1 ± 91.3[J, LH, LU]
Peak rear hip joint angular velocity (deg/s)	324.3 ± 91.2[LH, LU]	378.9 ± 141.6[LH, LU, RU]	212.1 ± 73.9[J, C, RH, LU, RU]	392.8 ± 141.7[LH]	232.9 ± 57.0[J, C, RH, RU]	489.3 ± 121.4[LH, LU]
Peak shoulder joint angular velocity (deg/s)	691.1 ± 135.45[LU, RU]	534.5 ± 207.78[LH, RH, LU, RU]	845.6 ± 142.96[C, LU, RU]	948.9 ± 228.03[C]	1062.1 ± 186.16[J, C, LH]	1069.8 ± 104.50 [J, C, LH]
Timing of peak shoulder joint angular velocity (% of movement)	87 ± 7	91 ± 8	92 ± 12	97 ± 2	96 ± 1	96 ± 1
Peak elbow joint angular velocity (deg/s)	560.6 ± 197.4	399.6 ± 171.8	527.5 ± 183.0	522.3 ± 212.5	651.0 ± 357.5	539.3 ± 139.9
Timing of peak elbow joint angular velocity (% of movement)	98 ± 2	99 ± 1	81 ± 10	84 ± 11	76 ± 5	75 ± 7
Peak fist velocity (m/s)	5.85 ± 0.85[C, LH, RH, RU]	6.97 ± 0.86[J, LH, RH, RU]	11.95 ± 1.84[J, C]	11.48 ± 1.90[J, C]	10.60 ± 2.30	11.55 ± 1.72[J, C]
Punch delivery time (ms)	405 ± 150[LH, RH, LU, RU]	495 ± 150	657 ± 145[J]	586 ± 0.96[J]	627 ± 103[J]	606 ± 100[J]

Note: Data is presented as mean ± SD.

[J] significantly different to the jab ($P < 0.01$).
[C] significantly different to the cross ($P < 0.01$).
[LH] significantly different to the lead hook ($P < 0.01$).
[RH] significantly different to the rear hook ($P < 0.01$).
[LU] significantly different to the lead uppercut ($P < 0.01$).
[RU] significantly different to the rear uppercut ($P < 0.01$).

Table 3.2b. Kinetic variable values of punch techniques.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Peak lead leg GRF (N/kg)	0.63 ± 0.17$^{C, LH, RH, LU, RU}$	1.06 ± 0.26$^{J, RU}$	1.09 ± 0.24^{J}	1.13 ± 0.20$^{J, RU}$	1.35 ± 0.27^{J}	1.35 ± 0.26$^{J, C, RH}$
Peak rear leg GRF (N/kg)	1.56 ± 0.35$^{C, LH, RH, LU}$	1.21 ± 0.27^{J}	0.96 ± 0.23^{J}	1.10 ± 0.23^{J}	1.15 ± 0.32^{J}	1.20 ± 0.28
Timing of peak lead leg GRF (% of movement)	80 ± 9	74 ± 7	71 ± 9	74 ± 6	73 ± 6	74 ± 5
Timing of peak rear leg GRF (% of movement)	64 ± 9	57 ± 11	63 ± 15	58 ± 9	67 ± 11	67 ± 8
Total lead leg net braking impulse (N/s/kg)	-10.1 ± 8.9$^{C, RH, LU}$	-62.5 ± 32.4^{J}	-32.6 ± 27.3^{RH}	-85.8 ± 37.8$^{J, LH, LU}$	-44.1 ± 20.8$^{J, RH}$	-64.4 ± 56.4
Total lead leg vertical impulse (N/s/kg)	89.7 ± 89.8$^{LH, RH, LU, RU}$	150.8 ± 77.1$^{LH, LU, RU}$	386.8 ± 160.2$^{J, C}$	248 ± 98.3^{J}	368.4 ± 120.9$^{J, C}$	297 ± 122.7$^{J, C}$
Total rear leg net propulsive impulse (N/s/kg)	29.2 ± 20.1$^{C, RH}$	66.6 ± 38.4$^{J, LH}$	17.7 ± 27.7$^{C, RH, LU}$	77.9 ± 34.7$^{J, LH}$	45.8 ± 25.2^{LH}	64.6 ± 54.3
Total rear leg vertical impulse (N/s/kg)	187.8 ± 121	239.3 ± 158.4	268 ± 141.8	255.3 ± 102	256.6 ± 115.8	258.1 ± 114.6

Peak lead ankle joint moment (N·m)	6.52 ± 1.6[C, LH, RH, RU]	9.61 ± 4.8[J, LH]	12.40 ± 2.4[J, C, RH, LU, RU]	8.50 ± 2.6[J, LH]	8.04 ± 3.1[LH]	9.47 ± 2.6[J, LH]
Peak rear ankle joint moment (N·m)	12.54 ± 2.7[LH, LU]	12.17 ± 3.8[LH, LU]	8.20 ± 4.6[J, C, RH, RU]	11.96 ± 3.4[LH, LU]	8.93 ± 2.9[J, C, RH, RU]	12.00 ± 2.5[LH, LU]
Peak lead knee joint moment (N·m)	60.28 ± 17.5[C, LH, RH, LU, RU]	161.17 ± 35.5[J, LU]	131.71 ± 23.1[J]	142.69 ± 38.9[J]	96.92 ± 22.6[J]	153.11 ± 27.5[J, LU]
Peak rear knee joint moment (N·m)	180.84 ± 33.3[LU]	170.38 ± 38.4	124.59 ± 28.3[J]	169.82 ± 21.8	148.54 ± 31.0	172.88 ± 29.5
Peak lead hip joint moment (N·m)	175.23 ± 23.8[LH, LU, RU]	181.54 ± 56.0[LU, RU]	223.16 ± 52.7[RH, LU, RU]	168.81 ± 39.7	112.85 ± 36.3[J, C, LH, RH]	116.56 ± 25.0
Peak rear hip joint moment (N·m)	201.78 ± 59.8[LH]	202.04 ± 40.4[LH]	143.31 ± 41.1[J, C]	156.81 ± 67.7	173.85 ± 54.9	189.50 ± 29.4

Note: Data is presented as mean ± SD.

[J] significantly different to the jab ($P < 0.01$).
[C] significantly different to the cross ($P < 0.01$).
[LH] significantly different to the lead hook ($P < 0.01$).
[RH] significantly different to the rear hook ($P < 0.01$).
[LU] significantly different to the lead uppercut ($P < 0.01$).
[RU] significantly different to the rear uppercut ($P < 0.01$).

3.3.3. Shoulder and elbow joint angular velocity

Punch type had a significant effect on peak shoulder joint resultant angular velocity ($F_{(2.2, 31.1)} = 32.7$, $P < 0.001$), with significantly higher values evident in the two uppercuts compared to the other punches ($P = 0.001$-0.046, ES = 1.0-1.7), apart from the rear hook ($P = 0.441$-1.0, ES = 0.3-0.7). The jab and rear-hand cross had the lowest peak resultant velocities of the six punch types at the shoulder joint (Table 3.2a). The timing of peak shoulder joint angular velocity occurred earliest in the jab (87 ± 7% of the movement), and latest in the rear hook (97 ± 2%).

Peak elbow angular velocities were consistently lower than observed at the shoulder, but interestingly, there was no overall difference in mean values among the punch types ($F_{(2.4, 32.9)} = 1.9$, $P = 0.167$). However, the highest value was again produced by one of the uppercuts (lead), and the lowest by the rear-hand cross. Lead and rear uppercuts achieved peak elbow joint angular velocity earlier than all other punch types, while the jab and rear-hand cross exhibited the latest peaks (Table 3.2a).

The jab and rear hand cross exhibited a proximal-to-distal sequence for the shoulder and elbow joints, respectively, with the shoulder reaching peak angular joint velocity approximately 12 % (jab) and 8.5 % (rear-hand cross) before the elbow (Figure 3.7). Meanwhile, hooks and uppercuts did not exhibit upper-limb proximal-to-distal sequencing as peak angular elbow joint velocity occurred before that of the shoulder joint across all hook and uppercut punch types (Figures 3.8 and 3.9).

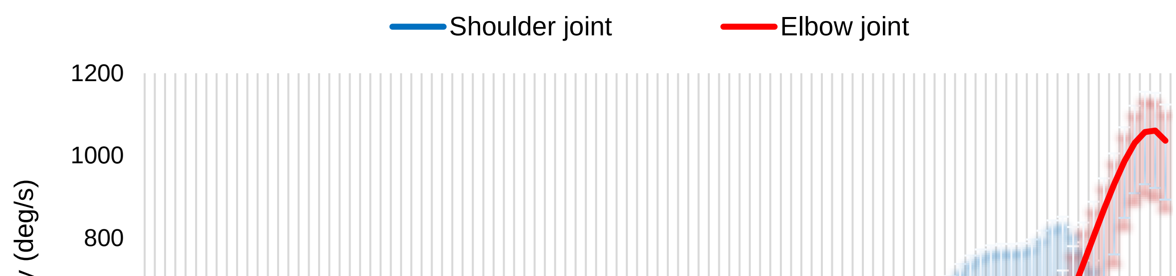

Figure 3.7. Mean (± SD) jab shoulder and elbow joint angular velocities from INITIATION to CONTACT.

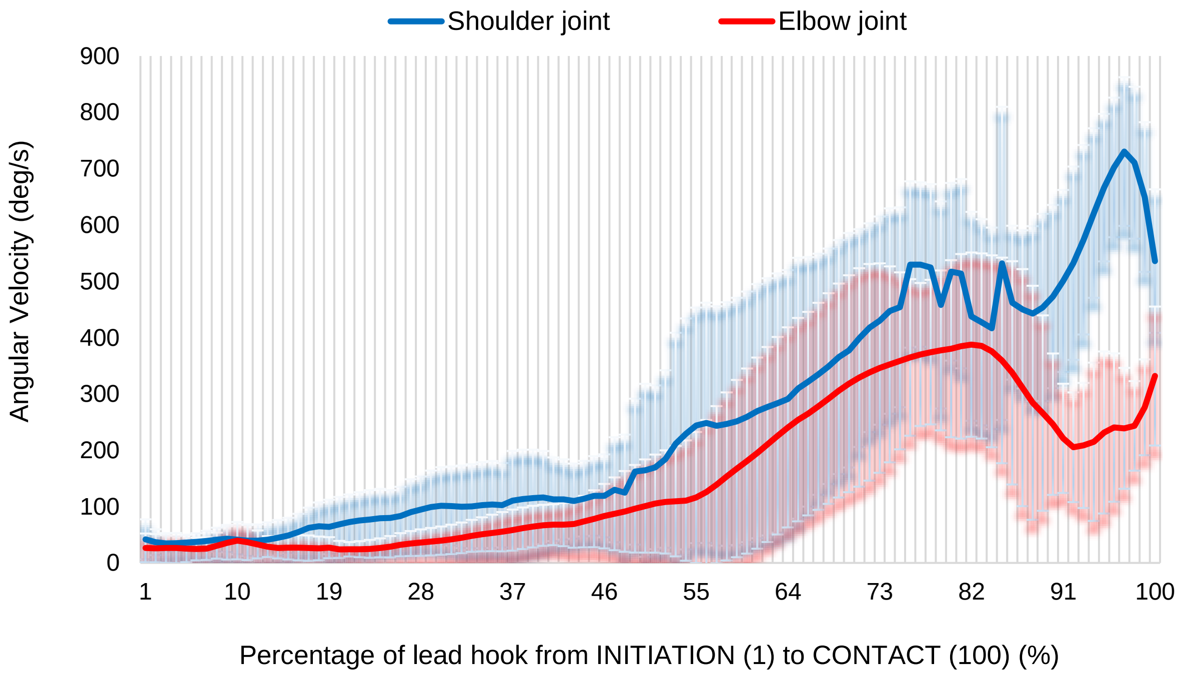

Figure 3.8. Mean (± SD) lead hook shoulder and elbow joint angular velocities from INITIATION to CONTACT.

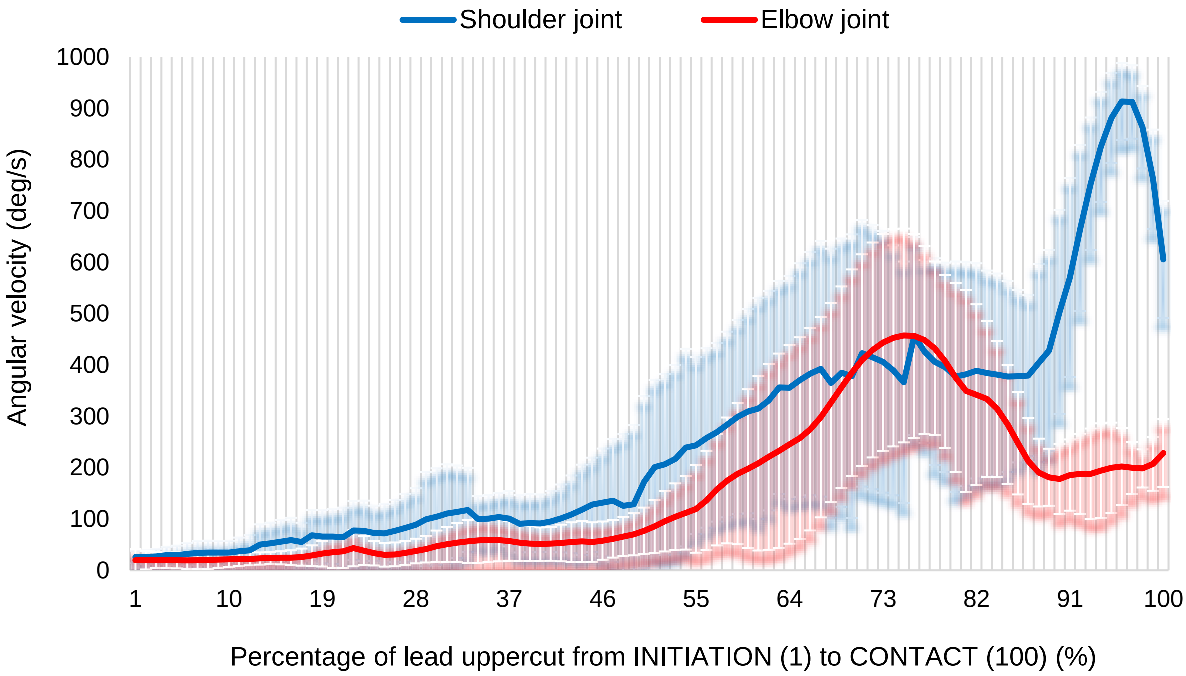

Figure 3.9. Mean (± SD) lead uppercut shoulder and elbow joint peak angular velocities from INITIATION to CONTACT.

3.3.4. Fist velocity and delivery time

The effect of punch type on peak resultant fist velocity was significant ($F_{(2.1,\ 29.8)}$ = 35.1, $P < 0.001$), with the highest (lead hook) exhibiting a value twice that of the lowest (jab). Post-hoc analysis (Table 3.2a) confirmed this difference and that between the jab and all the other punch types to be significant (P = 0.001-0.018, ES = 1.1-1.8). A significant punch type effect was noted for delivery time ($F_{(2.3,\ 41.4)}$ = 20.2, $P < 0.001$), principally on account of the jab's markedly shorter mean time than all other punch types ($P < 0.001$, ES = 1.2-1.3), except for the rear-hand cross (P = 0.034, ES = 0.6) (Table 3.2a). The lead hook took the longest to deliver, being 62% and 33% greater than the jab (ES = 1.3) and rear-hand cross (ES = 1.0), respectively.

3.3.5. Ground Reaction Force (GRF)

Peak resultant lead leg GRF was significantly different according to punch type ($F_{(3.6, 50.8)}$ = 32.5, P < 0.001), being largest in the lead and rear uppercut punches and smallest in the jab (Table 3.2b). Post-hoc analysis revealed the mean jab value to be significantly lower than all the other punches (P < 0.001, ES = 1.2-1.6). Punch type was also influenced for peak resultant rear leg GRF ($F_{(3.02, 42.31)}$ = 14.2, P < 0.001), with the jab producing the greatest value (Figure 3.10), being significantly higher than all other punch types (P = 0.001-0.004, ES = 0.8-1.4), except for the rear uppercut (P = 0.037, ES = 0.8). Differences of approximately 100 N were apparent between the two hook punches (lead and rear, ES = 0.6) and between the two uppercuts (lead and rear, ES = 0.4), but neither were significant. The comparison of peak lead and rear leg resultant GRF across punch types was significant for the jab punch only ($t_{(14)}$ = -11.7, P < 0.001, ES = 1.6). Furthermore, peak vertical GRF accounted for a larger degree of the total peak GRF than anteroposterior or mediolateral GRF for both lead and rear legs across all punch types (Figure 3.11).

The timing of peak lead leg GRF occurred earliest in the lead hook (71 ± 9% of the movement), and latest in the jab (84 ± 7%). The rear-hand cross generated the earliest peak rear leg GRF (56 ± 9% - see Figure 3.10) across punch types, while the lead uppercut exhibited the latest peak (71 ± 7%).

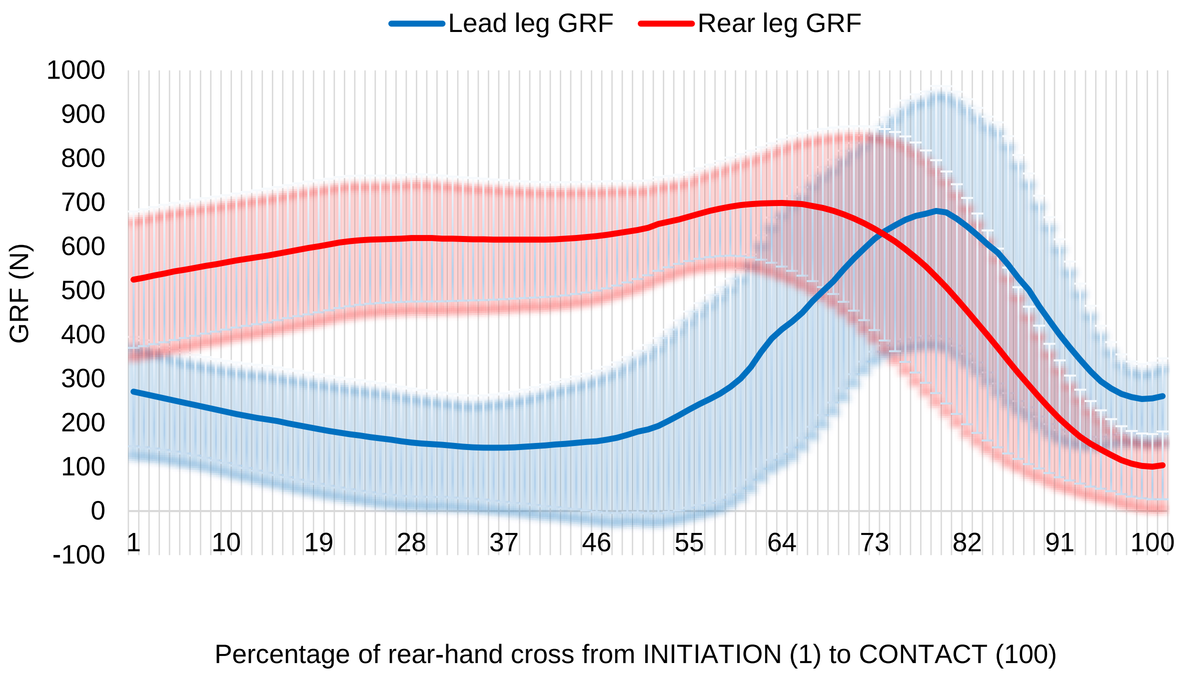

Figure 3.10. Mean (± SD) rear-hand cross peak lead and rear leg GRF from INITIATION to CONTACT.

The effect of punch type on lead leg net braking impulse was significant ($F_{(2.44, 34.1)}$ = 13.9, P < 0.001), with the highest (rear hook) exhibiting a value more than eight times that of the lowest (jab) (ES = 1.6). Post-hoc analysis (Table 3.2b) confirmed this difference to be significant, as were the differences between the jab and rear-hand cross, and lead uppercut (P < 0.001, ES = 1.5-1.6). Differences between the lead hook and rear hook were also significant (P < 0.001, ES = 1.3). Additionally, punch type had a significant effect on lead leg vertical impulse ($F_{(3.3, 46.8)}$ = 26.4, P < 0.001), with the jab and rear-hand cross (which had the lowest lead leg vertical impulse values), significantly different to the lead hook and both uppercuts (P = 0.001-0.002, ES = 1.2-1.6), but not each other.

A significant punch type effect was noted for rear leg net propulsive impulse ($F_{(2.8, 39.7)}$ = 9.8, P < 0.001), primarily resulting from the notably lower impulse value exhibited by the lead hook compared to the rear-hand cross, rear hook, and lead uppercut (P = 0.001-0.002, ES = 1.0-1.4). No significant differences were observed for rear leg vertical impulse according to punch type ($F_{(3.1, 43.0)}$ = 1.5, P = 0.099), with four of the six punch types exhibiting comparable values (Table 3.2b). Post-hoc analysis revealed the largest difference was between the jab and lead hook, but this was not significant (P = 0.35, ES = 0.6).

3.3.6. Ankle, knee and hip joint moments

Peak lead ankle extensor joint moment was significantly different according to punch type ($F_{(2.8, 39.8)}$ = 49.6, P < 0.001), being largest in the lead hook and smallest in the jab (Table 3.2b). Post-hoc analysis revealed the mean jab value to be significantly lower than all other punches (P < 0.001, ES = 1.0-1.6), except for the lead uppercut (P = 0.066, ES = 0.6). Punch type was also influenced for the rear ankle ($F_{(3.02, 42.31)}$ = 14.2, P < 0.001), with the jab producing the largest peak extensor value which was significantly greater than the lead hook and lead uppercut (P < 0.001, ES = 1.1-1.2), but not the rear-hand cross, rear hook or rear uppercut (P < 0.001, ES = 0.1-0.2) (Table 3.2b).

A significant punch type effect was noted for peak lead knee joint extensor moment ($F_{(3.5, 49.4)}$ = 30.0, P < 0.001), primarily on account of the jab's markedly lower peak value than all other punch types (P < 0.000-0.002, ES = 1.5-1.7) (Table 3.2b). Peak rear knee joint extensor moment also exhibited a significant punch type effect ($F_{(3.7, 52.6)}$ = 35.6, P < 0.001), though the only the jab and lead hook were different to each at a level of significance (P = 0.008, ES = 1.2).

The effect of punch type on peak lead hip joint extensor moment was significant ($F_{(2.6,\ 36.5)} = 18.0$, $P < 0.001$), with the highest peak (lead hook) almost twice that of the lowest (lead uppercut). Post-hoc analysis (Table 3.2b) confirmed this difference and that between the lead hook and rear uppercut to be significant ($P = 0.002$-0.007, ES = 1.4-1.5). For the rear hip, punch type effect was also significant ($F_{(3.5,\ 49.9)} = 7.8$, $P < 0.001$), with the rear-hand cross exhibiting a significantly higher extensor moment than the lead hook ($P = 0.011$, ES = 1.1), but no other punch types.

3.3.7. Relationship between peak resultant fist velocity and GRF, impulse, and kinematic variables

Peak lead leg resultant GRF correlated with peak resultant fist velocity ($r = 0.56$) and peak shoulder joint resultant angular velocity ($r = 0.55$) of the lead hook (Table 3.3). Furthermore, peak elbow joint resultant angular velocity was strongly associated with jab ($r = 0.78$) and lead hook peak ($r = 0.57$) fist velocities, respectively. All other associations were generally weak and non-significant.

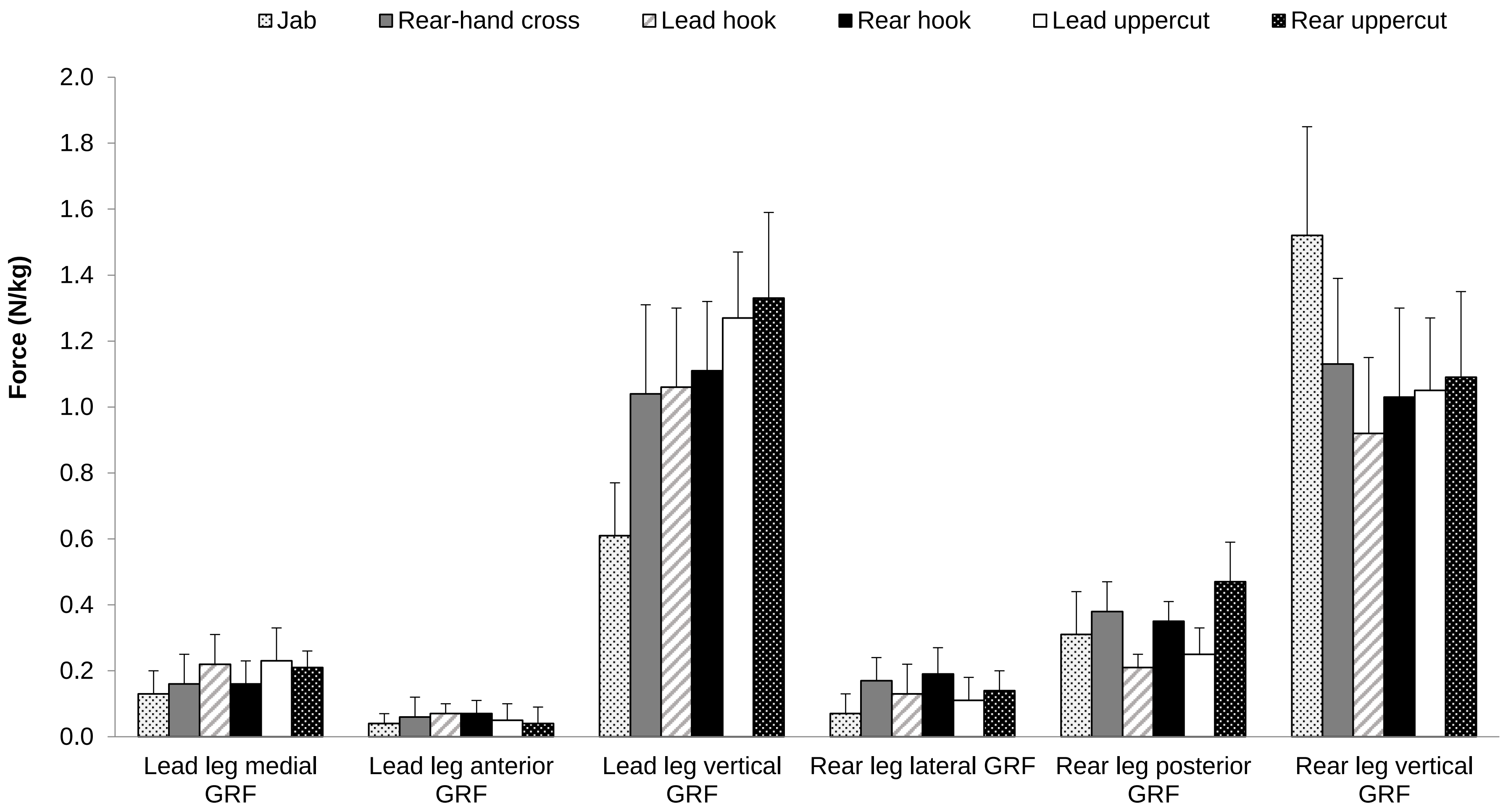

Figure 3.11. Peak lead and rear leg GRF (mean + SD) in mediolateral, anteroposterior, and vertical planes of motion across punch types (in accordance with the laboratory co-ordinate system).

Table 3.3. Pearson correlations (± 95% CI) between peak resultant fist velocity (FV) and kinematic and kinetic variables.

	Jab FV	Rear-hand cross FV	Lead hook FV	Rear hook FV	Lead uppercut FV	Rear uppercut FV
Peak shoulder joint angular velocity (deg/s)	0.35 (-0.20 to 0.91)	0.05 (-0.54 to 0.65)	**0.55*** (0.05 to 1.05)	0.40 (-0.14 to 0.95)	0.08 (-0.51 to 0.68)	-0.04 (-0.64 to 0.55)
Timing of peak shoulder joint angular velocity (% of movement	-0.33 (-0.90 to 0.22)	0.12 (-0.47 to 0.71)	0.02 (-0.57 to 0.62)	-0.20 (-0.79 to 0.38)	0.02 (-0.57 to 0.62)	0.009 (-0.59 to 0.60)
Peak elbow joint angular velocity (deg/s)	**0.78*** (0.31 to 1.13)	0.02 (-0.57 to 0.61)	**0.57*** (0.08 to 1.06)	0.19 (-0.39 to 0.78)	-0.23 (-0.81 to 0.35)	-0.16 (-0.75 to 0.42)
Timing of peak elbow joint angular velocity (% of movement)	-0.16 (-0.75 to 0.43)	0.28 (-0.29 to 0.85)	-0.27 (-0.84 to 0.30)	0.05 (-0.54 to 0.64)	-0.29 (-0.87 to 0.27)	-0.28 (-0.86 to 0.28)
Punch delivery time (ms)	0.45 (-0.07 to 0.98)	0.34 (-0.22 to 0.90)	-0.41 (-0.96 to 0.13)	0.39 (-0.15 to 0.94)	-0.08 (-0.68 to 0.51)	0.18 (-0.40 to 0.77)
Peak lead leg GRF (N/kg)	-0.24 (-0.82 to 0.34)	0.12 (-0.47 to 0.71)	**0.56*** (0.07 to 1.06)	0.28 (-0.28 to 0.86)	0.22 (-0.36 to 0.80)	-0.09 (-0.68 to 0.50)
Peak rear leg GRF (N/kg)	0.11 (-0.48 to 0.70)	0.35 (-0.20 to 0.91)	0.10 (-0.48 to 0.70)	0.28 (-0.28 to 0.86)	-0.46 (-0.99 to 0.06)	-0.05 (-0.65 to 0.54)
Total lead leg net braking impulse (N/s/kg)	0.30 (-0.26 to 0.87)	0.46 (-0.88 to 0.25)	0.25 (-0.41 to 0.76)	0.33 (-0.90 to 0.22)	0.21 (-0.39 to 0.77)	-0.51 (-1.02 to 0.00)
Total lead leg vertical impulse (N/s/kg)	0.12 (-0.58 to 0.61)	-0.13 (-0.14 to 0.95)	0.06 (-0.85 to 0.29)	0.39 (-0.16 to 0.94)	0.04 (-0.62 to 0.57)	-0.20 (-0.79 to 0.37)
Total rear leg net propulsive impulse (N/s/kg)	0.41 (-0.12 to 0.96)	0.35 (-0.27 to 0.87)	0.09 (-0.92 to 0.18)	0.33 (-0.22 to 0.90)	0.10 (-0.98 to 0.08)	**0.53*** (0.02 to 1.03)
Total rear leg vertical impulse (N/s/kg)	0.47 (-0.05 to 1.00)	0.35 (-0.24 to 0.89)	0.04 (-0.99 to 0.06)	0.25 (-0.32 to 0.83)	0.12 (-1.00 to 0.04)	-0.07 (-0.67 to 0.52)

***** denotes statistically significant at *P* < 0.05 level.

3.4. Discussion

3.4.1. Kinematic variables

The superior peak fist velocities of hook punches over straights and uppercuts corroborate the findings of Piorkowski at al. (2011) who also noted lead and rear hook generated greater fist velocities than the jab and rear-hand cross, respectively. This can be explained by the greater range of motion available at the shoulder joint in comparison to the elbow (Piorkowski et al., 2011; Loturco et al., 2016; Whiting et al., 1988) and that hook punches also have a longer trajectory and subsequent acceleration pathway, facilitating the generation of greater end-point fist velocities than straight punches (Piorkowski, 2009). In contrast to Piorkowski et al. (2011), the lead hook, and not the rear hook, exhibited the greatest peak resultant fist velocity of all punch types. This conflict is likely a consequence of the computer-based scoring system used in 2011. That is, a high frequency of jab punches alongside an ‘effective’ rear hand punch, particularly the rear hook (Davis et al., 2013; 2015) was favoured for points scoring. Accordingly, the boxers assessed in Piorkowski et al. (2011) probably possessed greater technical competency for the rear hook than those in the present study. Under the current scoring system (‘10-point must’), boxers execute lead hook punches more frequently (Davis et al., 2018; Thomson & Lamb, 2016), and likely possess an improved aptitude for this technique.

A notable finding was that of the rear uppercut generating greater peak fist velocities than both the rear-hand cross and rear hook. Such punches are deemed to be the hardest to master in boxing (Kapo et al., 2008), and are the most infrequent punch type observed in competition (Davis et al., 2018) owing to the close proximity between boxers and their counter-attacking nature (Hristovski et al., 2006; Thomson

& Lamb, 2016). Cabral et al. (2010) suggested that the high fist velocities generated by the rear uppercut occur as a result of a forceful proximal-to-distal sequence. Whilst such sequencing also plays a role in straight (Cheraghi et al., 2014) and hook (Piorkowski et al., 2011) punches, the position of the punching arm relative to the centre of mass during a rear uppercut is likely optimal for generating muscular torque at the shoulder joint (Cabral et al., 2010).

The shortest delivery times across all punch types were observed in the straight punches owing to their linear trajectory from the 'guard' position and travelling the least distance to the target (Piorkowski et al., 2011). As expected, the jab possessed the lowest delivery time, which in part explains why it is the most frequently executed punch within competition (Davis et al., 2013; 2015; 2018; El Ashker, 2011; Kapo et al., 2008; Thomson & Lamb, 2016). As a consequence, it can be employed in various ways; to judge and/or maintain the distance between opponents (limiting their counter-attacking opportunities), facilitate a positive impression among judges and create opportunities to land more forceful punches (such as the rear-hand cross or lead hook) (Haislet, 1968; Markovic et al., 2016), and provide an opponent with less time to defend/evade it, increasing its likelihood of landing cleanly (Piorkowski et al., 2011).

That hook and uppercut delivery times were not significantly different for both lead and rear hand variations was interesting, given that, regardless of ability level, the uppercut is the least frequently used punch in competition (Davis et al., 2018; El Ashker, 2011; Thomson & Lamb, 2016). Therefore, as uppercuts possess similar delivery time to hooks and can cause considerable 'damage' to an opponent resulting from their vertical trajectory (i.e. travel underneath an opponent's line of vision), unpredictability (due to their limited use in competition), and large impact forces (Arus, 2013; Cabral et al., 2010; Slimani et al., 2017; Thomson & Lamb, 2016; Viano et al., 2005), coaches and boxers should take heed of this finding and consider an increased application of uppercuts in training and competition.

Perhaps unsurprisingly given the above observation, both types of uppercut exhibited the greatest peak values for shoulder-joint angular velocity, with the lead uppercut also generating the highest peak elbow-joint angular velocity values of all punch types. As the kinematics of the lead uppercut have not been described previously, this is a novel finding.

However, with regards to the timings of peak shoulder and elbow joint angular velocities, only straight punches (jab and rear-hand cross) exhibited a proximal-to-distal sequence of the upper limbs. This is in agreement with previous studies that have reported shoulder angular velocity peaks prior to the elbow during the rear-hand cross (Cheraghi et al., 2014; Turner et al., 2011). That such a sequence was evident for the jab also has not been observed before. It is suggested that hooks and uppercuts failed to exhibit a proximal-to-distal sequence due to the 'fixed' elbow positions associated with these punch types. Indeed, during straight punches, the elbow joint rapidly extends after the punching arm has already started accelerating towards the target via angular velocities generated at the shoulder joint (Cheraghi et al., 2014; Jessop & Pain, 2016). However, during hooks and uppercuts, the elbow is flexed to a 'fixed' ~90° angle whilst the shoulder exhibits a rapid combination of abduction followed by flexion, protraction, and adduction from INITIATION to CONTACT, which may explain why peak angular velocities at the shoulder joint were markedly higher than those at the elbow across hooks and uppercuts. Consequently, it appears peak elbow joint angular velocity occurs prior to the elbow's ~90° position during hooks and uppercuts, and may assist in generating additional kinetic energy that, in conjunction with the angular velocities generated at the shoulder, accelerate the fist rapidly towards the target.

The peaks and timing of peak angular joint velocities for the shoulder and elbow, respectively, provide noteworthy information regarding the role of each joint across different punches and the degree to which they contribute to the end product of a punch (fist velocity and delivery time). This data provides useful information for coaches and boxers that may assist in the development of RT strategies. More specifically, RT strategies designed to augment angular velocities generated at the shoulder and elbow across various punch-specific positions (e.g. shoulder abducted to 90° relative to the torso for lead and rear hooks), and subsequently, the 'damage' potential of specific punch types, ought to be implemented.

3.4.2. Kinetic (GRF, impulse and joint moments) variables

Based on previous studies which have highlighted the importance of the lead leg to lead hand punches and the rear leg to rear hand punches (Cheraghi et al., 2014; Turner et al, 2011; Yan-ju et al., 2013), it was expected that the lead leg would produce greater GRF during lead hand punches, and likewise rear leg for rear hand punches. However, the current findings revealed that uppercuts (lead and rear) generated the greatest peak resultant GRF values for the lead leg across punch types (see Table 1). Moreover, it was interesting to find that both uppercuts produced greater peak lead leg resultant GRF values than straight and hook punches. In the absence of related research to assist interpretation for this finding, it is suggested that force orientation is a contributory factor in such movements (Bahamonde & Knudson, 2001; Morin, Edouard, & Samozino, 2011; Plessa, Rousanoglou, & Boudolos, 2010). That is, uppercuts (lead and rear) may generate the greatest peak lead leg resultant GRF owing to the larger peak lead leg vertical GRF values recorded for these punch types (in comparison to straights and hooks), alongside the predominantly vertical trajectory of the fist and a potential symbiotic relationship between these two characteristics.

That the rear uppercut generated higher peak lead leg resultant GRF than the jab and lead hook, respectively, was unexpected, as was the lead hook producing the greatest vertical impulse, while the rear hook generated the largest net braking impulse. It is possible that these findings relate to the influence of the lead leg in producing a stable base from which to generate force proximally to the distal segments (i.e. the fist) (Cabral et al., 2010). Such a role has been reported for other activities requiring movements with lower-body kinematics similar to those of rear hand punches (i.e. triple extension of the hip, knee and ankle; trunk rotation; rapid projection of the arm). For example, Bartonietz (1994) noted that the lead leg produced forces up to three times that of the rear leg in shot putting (no values though reported), while McCoy et al. (1984) determined ~95% of 'shot velocity' (i.e. velocity of the shot put when released from the hand) was influenced by vertical braking forces produced by the lead leg. Furthermore, the majority of lead leg GRF and impulse was concentrated in a vertical direction (see Table 1 and Figure 11), which is similar to findings observed in the above activities and baseball pitching (MacWilliams, Choi, Perezous, Chao & MacFarland, 1998). The considerable vertical GRF, net braking, and vertical impulse result from the extensive braking demands (rapid eccentric muscular contractions to prevent excessive knee flexion) that assist in facilitating the propulsive vertical forces generated by the rear leg to travel superiorly to the distal segments of the body (i.e. fist/hand) (Williams, 2012). This corroborates previous boxing research which has highlighted that during the rear-hand cross punch, the ability of a boxer to maintain a rigid lead leg (through the production of vertical anterior-posterior braking forces (i.e. impulse)), generation of lower-limb joint extensor moments and extension angular velocities, and ability to control the degree of lead knee flexion (i.e. production of isometric force to limit excessive/unwanted flexion) may assist in the transmission of force from the lower limbs to the arm/hand segments via the kinetic chain (Cheraghi et al., 2014; Turner et al., 2011). The current findings suggest the braking forces (GRF and impulse) and stabilisation of the lead leg, in addition to lead hip, knee and ankle joint extension angles, angular extension velocities and extensor moments, play a role in the execution of both lead and rear uppercuts, and that they are more evident than for the rear-hand cross.

The observed higher GRF values of the rear leg, rear-hand cross, rear hook and rear uppercut techniques relative to the lead hook and lead uppercut, confirm the importance of the rear leg to rear hand punches noted previously (Cheraghi et al., 2014; Filimonov et al., 1985; Gulledge & Dapena, 2008; Turner et al. 2011). However, that the rear leg produced ~71% of the total GRF during the jab, greater than for any other punch type, was a novel finding. It is therefore plausible to suggest that the jab is less reliant on trunk rotation and upper-body stretch-shortening cycle characteristics, and instead, requires a high degree of rear leg resultant GRF to propel the fist rapidly along the anterior-posterior axis towards the opponent/target. This theory is supported by the rear hip, knee and ankle joint extensor moments, peak rear knee and ankle joint extension angles and extension velocities, respectively, of which were all greatest for jab in comparison to all other punch types. Indeed, torque and GRF generated by the rear leg is likely to have transmitted force through the kinetic chain via a sequence of ankle, knee and hip joint extensions and extensor moments that culminated in the rapid projection of the lead fist to the target with a lesser reliance on upper-extremity SSC characteristics. Indeed, in the example of the jab, the rear leg produced peak GRF at 64% of the punch that is likely to have facilitated the sequential peaks in rear ankle (66%), knee (78%), and hip (80%) joint angular extension velocities, respectively. This is likely to have subsequently contributed to the generation of peak shoulder (87%), and elbow (98%) joint velocities, that assisted in projecting the punching fist to the punch target.

The peaks and timing of peak GRF for the lead and rear legs offer useful information concerning the role each leg across punch types and how they potentially influence other biomechanical variables (e.g. upper-limb kinematics). During the jab and rear hand punches (rear-hand cross, rear hook and rear uppercut), the timings of peak GRF appear to corroborate suggestions in previous research that force generated by the rear leg is the primary motion that initiates these techniques (Cabral et al., 2010; Cheraghi et al., 2014, Lenetsky et al., 2013; Turner et al., 2011). Indeed, it appears that rear leg GRF peaks first in order to produce momentum from the ground that initiates the generation of kinetic energy, from which the lead leg then peaks to provide a stable, rigid base that assists in facilitating the transfer of kinetic energy through the hips, trunk and upper-limbs (kinetic chain) with the assistance of lower-limb joint kinematics and moments. This is evidenced by the sequential timings of peak GRF for the rear-hand cross, whereby the rear leg (57%) generated peak forces prior to the lead leg (74%). Moreover, ankle (65%), knee (70%) and hip (72%) joint angular extension velocities of the rear leg peaked prior to those of the lead leg (ankle - 77%, knee - 81% and hip - 88%), respectively.

Meanwhile, for the lead hook and lead uppercut, GRF for the lead and rear legs peak in close proximity to one another, suggesting that both legs assist in the generation of force at similar time-points during the execution of these punches (as evidenced in the large lead and rear leg vertical impulses for these punch types). However, more specifically, lead hip extensor moments appear to influence the execution of the lead hook, with this punch type exhibiting the greatest peak value across all punch types. This finding, alongside the lead knee and ankle extensor moments, seems to imply the lead leg is the principal contributor to the generation of momentum and energy for lead hook, which likely occurs as a result of the lower-limb kinetic chain sequence. Indeed, this is supported by the timings of peak lower-limb joint extensor moments for the lead leg, whereby the ankle (76.2%) exhibited its peak moment prior to the knee (94.4%) and hip (98.2%), respectively. Interestingly, while the rear leg seems to assist in stabilising the body during the lead hook that fosters the sequential transfer of momentum from the feet to the punching fist, this is not the case for the lead uppercut. Indeed, the lead uppercut demonstrated larger peak rear hip, knee and ankle joint extensor moments than the lead hook, which also followed a kinetic chain joint sequence (ankle – 57.7%, knee – 73.4%, and hip – 75.6%). This potentially suggests the rear leg plays a larger role in the generation of force and momentum for the lead uppercut compared to the lead hook.

This information is useful for coaches and boxers as it may be used to develop relevant RT strategies that enhance the function of each leg during different punch types. For example, to enhance the performance of rear-hand punches, RT exercises/strategies that augment the lead leg's ability to absorb force and resist excessive knee flexion (e.g. bilateral and unilateral drop/depth jump landings, single leg bounds) and the rear leg's ability to forcefully extend the hip, knee and ankle joints (e.g. loaded jumps, heavy sled pushes), in addition to rear hip rotation (e.g. single arm landmine push presses) are recommended.

With regards to impulse, the lead hook generated the largest vertical impulse and the rear hook the largest net propulsive impulse for the rear leg, respectively. This appears to suggest that these two punches produced the highest forces over the duration of each punch from INITIATION to CONTACT. Previous research has reported the importance of impulse to explosive dynamic movements (Davies, Orr, Halaki, & Hackett, 2016; Suchomel & Sole, 2017), and, more specifically, that enhancing the braking (antero-posterior and vertical) impulse of the lead leg may increase the force of a punch owing to an increase in velocity, and subsequently momentum (mass x velocity) (Turner et al., 2011). Indeed, it is suggested that the greater the vertical and net propulsive impulse produced by the rear leg, the greater the overall momentum and peak fist velocities generated. This notion is somewhat supported by the significant rear leg propulsive impulse, rear hip, knee and ankle joint extension angles, extension velocities and extensor moments, and high peak fist velocity reported for the rear uppercut. Consequently, it seems reasonable to suggest that the more GRF a boxer can produce from the initiation of a punch to the point of impact with the target, the larger the degree of energy generated by the kinetic chain. In turn, this yields greater resultant joint angular velocities generated by the upper-limbs (shoulder and elbow) and linear velocity of the fist towards the target. . Boxers could develop such increases in rear leg force (GRF, impulse and joint moments) through regular technical practice with a focus on rear leg propulsion via rear hip, knee and ankle joint extension and rotation (Chapter 3). In addition, lower-body resistance exercises that emphasise force-time characteristics across sagittal (e.g. back squats, broad jumps), frontal (e.g. lateral lunges, sideways sled drags) and transverse (e.g. med-ball shot putt, overhead med-ball throw) planes may enhance the extension angles, angular extension velocities and extensor moments of the rear leg joints

(Chapter 3) that could augment linear, angular and rotational force generation (Lenetsky et al., 2013; Suchomel et al., 2016; 2018). Future research should investigate the role of impulse to maximal punching, its relationship to GRF during maximal punching, and assess whether enhancing this kinetic variable can improve the characteristics of maximal punching performance.

3.4.3. Relationships between kinematic and kinetic variables

As expected, lead hook peak resultant fist velocity exhibited a significant (moderate) relationship with peak lead leg resultant GRF, signifying the influence of the vertical GRF produced by the lead leg. Furthermore, the notable lead leg joint extension angles, angular extension velocities and extensor moments, sequence of peak joint moments, and apparent contribution of ankle, knee and hip joint musculature to the generation of kinetic energy and momentum during the lead hook offers additional information that reinforces the importance of the lower-limbs in the generation of high fist velocities. Indeed, the sequential peaks in ankle, knee and hip joint angular extension velocities and moments (in addition to the shoulder and elbow joint angular velocity peaks) appear to highlight the influence of the kinetic chain to this punch type. On this evidence, it is proposed that as part of boxing training/ traditional skill-based practice, boxers aiming to increase the velocity of the fist and the damage-causing capabilities of this punch attempt to focus deliberately on generating force through the lead leg, in addition to rapid rotations and extensions of the lead ankle, knee and hip joints, during the initiation and delivery of the lead hook. Also, as previous research has highlighted the importance of lower-body strength to maximal punching (Del Vecchio et al., 2017; 2019; Loturco et al., 2014, 2016; Pilewska et al., 2017; Zekas, 2016), coaches and boxers should consider the implementation of axial-loaded lower-body resistance exercises (e.g. squats, deadlifts, cleans, lunges) (Lenetsky et al., 2013; Turner et al., 2011) to enhance the peak vertical and resultant GRF potential of the lead leg, in addition to lead hip, knee and ankle extensor joint moments.

Peak shoulder joint angular velocity also exhibited a moderate relationship with peak lead hook fist velocity, confirming the findings of Piorkowski (2009). It has been suggested that rear-hand crosses (Karpilowski, Nosarzewski, Staniak, & Trzaskoma, 2001), lead and rear hooks (Piorkowski et al., 2011; Whiting et al., 1988), and lead and rear uppercuts (Cabral et al., 2010) produce a stretch-reflex (via the SSC) at the shoulder joint which potentiates the ensuing concentric muscular contraction, and subsequently, fist velocity. Therefore, it would appear that RT exercises that improve a boxer’s ability to rapidly abduct and adduct the punching arm may enhance the end-point velocity of the fist, and subsequently, its damage-causing potential. Furthermore, as the upper-body kinematics of punching comprise a multitude of joint motions, including shoulder adduction, abduction, flexion and extension (Cabral et al., 2010; Piorkowski et al., 2011), a boxer’s training regimen should aim to incorporate ballistic resistance exercises that enhance speed and velocity characteristics of the musculature (deltoid, pectoralis major and minor, latissimus dorsi, and serratus anterior) that facilitate such motions, alongside regular technical practice (Piorkowski et al., 2011; Turner et al., 2011; Veegera & Van Der Helma, 2007).

The significant association between peak elbow angular velocity and lead hook peak resultant fist velocity has not been documented in previous research, and it is suggested that, in a similar manner to the shoulder joint, the elbow joint exhibits a stretch-reflex following INITIATION that facilitates the generation of large peak fist velocities. Indeed, at the onset of INITIATION, the elbow may extend slightly from its flexed ~90° angle as the shoulder abducts before rapidly adducting as the fist is projected towards the target. Although further research is required to establish if kinetic and kinematic variables associated with maximal punching performance are optimised if the elbow joint is extended and flexed rapidly or fixed at a ~90° angle, enhancing the eccentric strength and SSC efficiency of the musculature surrounding the elbow joint would appear to increase stability and force production potential of the lead hook (Cormie et al., 2011a; Zatsiorsky & Kraemer, 2006).

Given the findings of Piorkowski et al. (2011) it was unsurprising to observe the link between peak jab resultant fist velocity and elbow joint angular. This likely occurs as a consequence of the jab often being less reliant upon SSC characteristics at the shoulder joint and trunk in order to minimise its delivery time, and therefore enhance its likelihood of striking the opponent before they can defend/evade (Haislet, 1968; Hickey, 2006). It would appear that enhancing a boxer's ability to extend the punching arm as rapidly and forcibly as possible (elbow extension) may increase peak jab fist velocity, and consequently, could improve competitive performance considering the jab to the head of an opponent is the most frequently executed punch within competitive bouts (Davis et al., 2015; Davis et al., 2018; Thomson & Lamb, 2016). Moreover, increasing the rate of force development (RFD) of the elbow extensors (via elastic RT) has been shown to improve peak jab velocity as much as 11% ($P < 0.01$) in competitive boxers, (Markovic et al., 2016). Therefore, it is recommended that boxers include resistance exercises in their training programme that increase the strength of the tricep brachii musculature (primary muscle group responsible for elbow extension) to improve elbow joint velocity, and subsequently, peak jab fist velocity.

3.4.4. Conclusion

In appraising the kinetic and kinematic characteristics of six traditional punch techniques implemented within amateur boxing, the present study has revealed that: (i) the lead hook produced the greatest peak resultant fist velocity values; (ii) the jab recorded the shortest delivery time; (iii) peak lead and rear leg resultant GRF were comparable across all punch types except for the jab, with force primarily applied in a vertical direction; (iv) the lead hook generated the largest peak extension angles and angular extension velocities for the lead ankle, knee and hip joints; (v) the jab produced the largest peak rear ankle and knee joint extension angles and angular extension velocities; (vi) peak lead ankle and hip joint moments were greatest for the lead hook; (vii) peak rear ankle and knee joint moments were largest for the jab; and (viii) punch-specific inter-relationships exist between peak fist and joint angular velocities, and peak fist velocities and GRF. Whilst these findings advance our biomechanical understanding of maximal punching, there is now scope to investigate the consistency (MV) of these variables, and the links between boxer's physical qualities and the key kinetic and kinematic variables, leading potentially to the development of punch-specific strength and conditioning strategies.

Chapter 4

Movement variability of maximal effort punches among amateur boxers

Abstract

The purpose of this study was to quantify the within-subject (intra) and between-subject (inter) variability of maximal effort punch (jab, rear-hand cross, lead and rear hook, lead and rear uppercut) kinetics and kinematics among amateur boxers. This study also sought to appraise the impact of boxing experience on the within-subject variability of maximal punch biomechanics. Fifteen male boxers (age: 24.9 ± 4.2 years, stature: 178 ± 8.0 cm; body mass: 75.3 ± 13.4 kg; years of experience: 6.3 ± 2.8 years) performed maximal effort punches against a suspended punch bag during which upper-body kinematics were assessed using a 3D motion capture system and lower-body (lead and rear legs) kinetics were recorded via two force plates. Within-subject variability was moderate-to-high for all kinetic and kinematic variables across all punch types (≥ 5%), with analysis revealing significant ($P < 0.05$, $d = 0.2$-1.9) differences for delivery time, peak fist velocity, timing of elbow joint angular velocity, and peak lead leg GRF. Between-subject variability was high (> 10%) across all punch types and biomechanical variables, particularly for peak angular elbow joint velocity for the rear-hand cross (47.9%) and all lead and rear leg impulse variables (47.2-129.2%), respectively. Meanwhile, SWC% was lowest for the timing of peak elbow joint angular velocity (SWC% = 0.2%) during the rear-hand cross, and highest for jab lead leg vertical impulse (SWC% = 20.9%). No significant relationships ($P > 0.05$) were observed between years of experience and any biomechanical variable across punch types. While these findings advance our understanding of the movement variance of maximal punches and its association with boxing experience, future research pertaining to the influence of boxers' physical qualities on punch kinetics and kinematics is justified.

Key words: combat sports, boxing, punching, variation, experience

With the role of certain kinetic and kinematic variables to maximal punches having been quantified alongside their differences between punch types (Chapter 3), research is merited to establish the movement variability (MV) associated with these measures. Indeed, with the importance of biomechanical variables to maximal punches having been highlighted, this study will appraise the MV of key kinetic and kinematic qualities of maximal punches, across different punch types.

4.1. Introduction

Movement variability (MV) concerns the influence of intra- (trial-to-trial) and inter- (individual/human) movement variations on technique (Preatoni et al., 2013). Until recently, MV was deemed undesirable system 'noise/error', evidence of dysfunctional movement patterns, and an aspect of sports performance that decreases as skill proficiency increases (Bartlett, 2007; Bartlett et al., 2007; Langdown et al., 2012). Consequently, it was assumed by biomechanists and coaches alike that sports techniques/movement patterns should be invariant in order to optimise the performance of a given task, whilst training should foster a singular, all-encompassing technical model (Bartlett, 2007; Newell & Corcos, 1993). However, research into MV has reported how skilled-athletes may in fact utilise movement variance as a way of optimising athletic performance (Bartlett, 2007; Wagner et al., 2012).

Indeed, the execution of dynamic full-body skills and actions across various sports, including handball (Wagner et al., 2012), basketball (Button et al., 2003; Robins, Davids et al., 2008; Schmidt, 2012), volleyball (Handford, 2006), triple jump (Scott et al., 1997) and javelin (Morriss et al., 1997) have highlighted the crucial role of MV to successful performance outcomes. MV appears important to achieving performance outcomes owing to the inter-subject characteristics of performers, whereby different athletes often execute the same movements with varying techniques whilst still achieving the same outcomes (Bartlett et al., 2007). Therefore, performers should avoid imitating the technique and/or training practices of other successful athletes as this may not be the optimised movement pattern given the characteristics of their individual structural (anthropometric), functional (physiological and psychological), and task (pre-determined requirements of a competition or skill performance) constraints (McGarry et al., 2013). It has also been suggested MV is critical to allow performers to modify the coordination of their actions and facilitate effective adaptation to environmental and/or competitive changes (Handford et al., 1997; Orth et al., 2018), though the existence of a trade-off between functional and detrimental MV in terms of optimal performance has yet to be established (Langdown et al., 2012).

In acknowledging MV as a likely desirable feature of technique therefore (Bartlett et al., 2007), it is surprising that its role in sports performance and maximal boxing punching in particular, has received limited attention to date. Given the unpredictability of opponents and the ballistic nature of maximal punching itself, MV could provide boxers with purposeful solutions to what is a complex environment. Indeed, when punching a target, boxers must concurrently judge the distance to the target, select the specific technique to utilise, and assess how forcefully to perform the punch whilst the opponent/target is still within 'punching range' (Choi & Mark, 2004; Hristovski et al., 2006). Particular characteristics of boxing add to these sources of punch MV (Davids et al., 2006), such as the boxer's arm segment dimensions (limb lengths), pre-fight strategy, fighting 'style', and perceived efficiency (perception of own performance capability). Accordingly, it has been suggested that compensatory and varying kinematics during the execution of a skill is actually symptomatic of skilled performance as performers intentionally modify their movements in order to adapt to environmental and/or competitive situations (Bartlett, 2007; Button et al., 2003; Hanford, 2006; Wagner et al., 2012).

Conflicting evidence has demonstrated unintended MV is more prevalent in novice performers, and in their case detrimental to the performance outcome of the movement skills/techniques, including baseball pitching (Fleisig, Chu, Weber, & Andrews, 2009), golf swing (Bradshaw et al., 2007), and punching (Lenetsky et al., 2017). While Lenetsky et al. (2017) identified small-to-moderate variability for punch impact kinetics, the extent of MV and its influence on the upper-body kinematics and lower-body kinetics of maximal punching are currently unknown. Research has yet to elucidate whether different punch types exhibit more MV than others, and why this might occur. Given Chapter 3 (Study 1) revealed substantial biomechanical differences between punch types, it follows MV might be equally diverse. Generating such data would facilitate an understanding of the biomechanical qualities underpinning maximal punching, and consequently inform punch-specific practices for the benefit of competition. Moreover, recognising the degree of MV associated with different punch types will be valuable for identifying the occurrence of meaningful changes in maximal punching characteristics following technique- or strength-related interventions. That is, since boxers continually train kinematic and kinetic features of punching (Bingul et al., 2017), the ability to monitor technique accurately and determine genuine adjustments owing to interventions, rather than temporal fluctuations in technique, would provide useful information to document a boxer's progression (Hopkins, Hawley, & Burke, 1999; Hopkins, 2004; Preatoni et al., 2013). To this end, quantifying the *responsiveness* (c.f. smallest worthwhile change) of a test allows practitioners to determine the minimum change in any given aspect of performance that must be realised before determining a genuine improvement, or deterioration, has taken place (Impellizzeri & Marcora, 2009). Such analysis addresses the practicality of a measure, which can take precedence over statistical significance (Buchheit, 2016). Therefore, the primary aim of this study was to quantify the within-subject (intra) and between-subject (inter) variability of maximal effort punch kinetics and kinematics among amateur boxers. Additionally, the study sought to assess the impact of boxing experience on the within-subject variability of each biomechanical variable.

4.2. Methods

4.2.1. Participants

Fifteen males (age: 24.9 ± 4.2 years; stature: 177.9 ± 8.0 cm; body mass: 75.3 ± 13.4 kg; experience: 6.3 ± 2.8 years) across seven weight categories (flyweight (49-52 kg) to super-heavyweight (91+ kg)) were recruited from six amateur boxing clubs located across the North West of England, based upon current boxing experience (≥ 2 years) and official bout history (≥ 2 bouts). As all data within the current study was obtained through the research presented in Study 1 (Chapter 3), all participants completed a health screening questionnaire (PAR-Q) and supplied written informed consent, while Institutional ethical approval was granted by the Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee.

4.2.2. Design

The study adopted a cross-sectional, repeated measures design to assess the within-subject and between-subject variability of kinematic variables, GRF and impulse of the primary punch techniques observed in boxing competition (Thomson & Lamb, 2016). The dependent variables were punch delivery time, peak resultant fist velocity, peak shoulder joint resultant angular velocity, peak elbow joint resultant angular velocity and timings of peak shoulder and elbow joint resultant angular velocities (kinematic -

sampled at 300 Hz), and peak lead and rear leg resultant GRF, lead leg net braking and vertical and rear leg net propulsive and vertical impulse (kinetic - sampled at 900 Hz) characteristics measured via a 3D motion capture system (Oqus 7+ system, Qualisys Inc., Gothenburg, Sweden) and two embedded force platforms (model 9281CA with 600 x 400 mm internal amplifiers, Kistler Instruments, Hampshire, UK), respectively (see Chapter 3 for a detailed description). The independent variables were punch type (jab, rear-hand cross, lead hook, rear hook, lead uppercut, and rear uppercut) and years of boxing experience.

4.2.3. Procedures

All participants performed punches against a water-filled punch bag (9-inch diameter - Aqua Bag 'Headhunter' model, Aqua Training Bag, New York, United States; see Chapter 3) while wearing reflective markers placed at specific anatomical landmarks to assess the full-body kinematics in 3D spaces across six degrees of freedom. Kinematic and kinetic data was quantified via Qualisys Track Manager (QTM) (Version 2.14, Qualisys Inc., Gothenburg, Sweden) and subsequently analysed using Visual 3D (Version 6, C-Motion Inc., Rockville, United States). Five trials were performed for each punch type based upon recommendations in previous research (Bartlett, 2007; Bates, Dufek & Davis, 1992; James, Herman, Dufek & Bates, 2007) (see Chapter 3 for a more detailed description of the punch assessment procedure).

4.2.4. (Relative) Sequential analysis

Relative sequential analyses were completed to highlight potential differences between trials and to verify the percentage of performance trials needed to achieve 'mean stability' (i.e. how many trials were needed for the mean value of each dependent variable to become consistent), with 0.25 standard deviation bandwidths used in accordance with previous literature to ensure a stringent moving average across trials (Gore, Marshall, Franklyn-Miller, Falvey, & Moran, 2016; Taylor, Lee, Landeo, O'Meara, & Millett, 2015). This method of analysis was implemented to establish if the number of trials per punch type in the current study was enough to obtain a 'stable' mean for the kinetic and kinematic variables examined. The relative sequential analysis score is quantified by dividing the number of trials to stability by the total number of trials of the condition from which it was taken (e.g. five rear-hand cross trials). This score can then assist in highlighting differences between conditions with regards to the percentage of maximum possible trials taken to achieve mean stability (Taylor et al., 2015). Analyses revealed across all kinetic and kinematic variables, mean stability was achieved between 40-60% of the five trials utilised per variable (i.e. 2-3 trials were determined 'enough' to achieve a stable mean). This illustrates that when assessing maximal punches, 2-3 trials appear adequate to obtain 'stable' kinetic and kinematic data using a 3D motion capture system and integrated force platforms. Examples from a randomly selected boxer can be observed in Figure 4.1. To ensure the sequential analyses was independent of the eventual trial number (i.e. five), further analyses were conducted with a single boxer whereby 30 trials were completed (with ample rest of 60 seconds between efforts). Such analyses reinforced that five trials were indeed suitable to scrutinise the biomechanics of maximal effort punching (Figure 4.2). Although the overall CV% of selected kinetic and kinematic variables exhibited 'high' variability (≥ 10%; Queen et al., 2006; Roberts & Priest,

2006) across the 30 trials (peak fist velocity - 13.5%, delivery time - 18.9%, peak shoulder joint angular velocity - 13.3%, and peak rear leg GRF - 10.4%), previous literature reported comparatively low variation in the number of recommended trials between subjects (Taylor et al., 2015). That is, during a biomechanical analyses of a ballistic action (throwing), the number of trials recommended via sequential analysis fluctuated by only ≈10% between subjects (Taylor et al., 2015). Of course, this suggests the five trials used might not have been suitable for all boxers though this alternatively suggests five trials was perhaps more than is necessary for other boxers. Clearly, corroborating the sequential analyses with several additional boxers would have been preferential, but in the absence of clear guidelines and with it being supplementary to the chapter, it was deemed appropriate to rely upon a single case to provide some indication that the number of trials completed for data collection was adequate.

4.2.5. Statistical analysis

The within-subject coefficient of variation (CV) was quantified to assess the variability of dependent variables between trials (Thomson & Lamb, 2016), by calculating the mean CV from individual subject CVs $[(standard\ deviation/mean) * 100]$ across each dependent variable (Hopkins, 2000). Between-subject variation was quantified to assess the variability of dependent variables between participants. This was calculated by dividing the standard deviation of group scores by the overall mean (Paton, & Hopkins, 2006). In accordance with previous literature, variability was categorised as ‘low’ (<5%), ‘moderate’ (5-9.9%) or ‘high’ (≥ 10%; Queen et al., 2006; Roberts et al., 2006; Thomson, 2015). The standard error of mean values (SEM% =

(SD / √ number of trials / mean) x 100) were quantified for the kinematic and kinetic measures of each boxer to assess the consistency of mean values across punch trials. The difference between within-subject CV and the standard error of the mean (SEM%) was used to quantify each boxer's biological variability (Biological coefficient of variation: BCV% = within-subject CV% - SEM%) (Bradshaw et al., 2007). A one-way repeated measures analysis of variance (ANOVA) was used to compare the CV% of biomechanical variables across punch types, with Bonferroni corrected *post-hoc* tests applied as necessary (significance accepted as $P \leq 0.003$). Pair-wise comparisons were quantified through Cohen's effect sizes, calculated as: $d = (\bar{x}1 - \bar{x}2) / SD$; where $\bar{x}1$ and $\bar{x}2$ represent the two sample means and SD the pooled standard deviation. The magnitude of Cohen's *d* effect sizes were classified as: trivial < 0.2, small 0.2-0.6, moderate 0.6-1.2, large 1.2-2.0, and very large > 2.0 (Hopkins, 2004). Additionally, Pearson product-moment coefficients with 95% confidence intervals were used to quantify the relationships between years of boxing experience and within-subject CV of kinematic and kinetic variables, with thresholds interpreted as: < 0.1 (trivial); 0.1-0.3 (small); 0.3-0.5 (moderate); 0.5-0.7 (large); 0.7-0.9 (very large) and > 0.9 (nearly perfect) (Hopkins, 2002). The smallest worthwhile change (SWC%) was also quantified to ascertain the minimum change required to identify 'genuine' differences in performance (Currell & Jeukendreup, 1998) using Cohen's (1988) standardised *d* (0.2 x pooled standard deviation of sample means); 'moderate' worthwhile change (MWC%) and 'large' worthwhile change (LWC%) were also calculated using three (0.6) and six (1.2) times the SWC% (Batterham & Hopkins, 2006; Hopkins, 2004; Waldron, Highton, & Twist, 2013). All statistics were completed using SPSS (version 23, Chicago, USA).

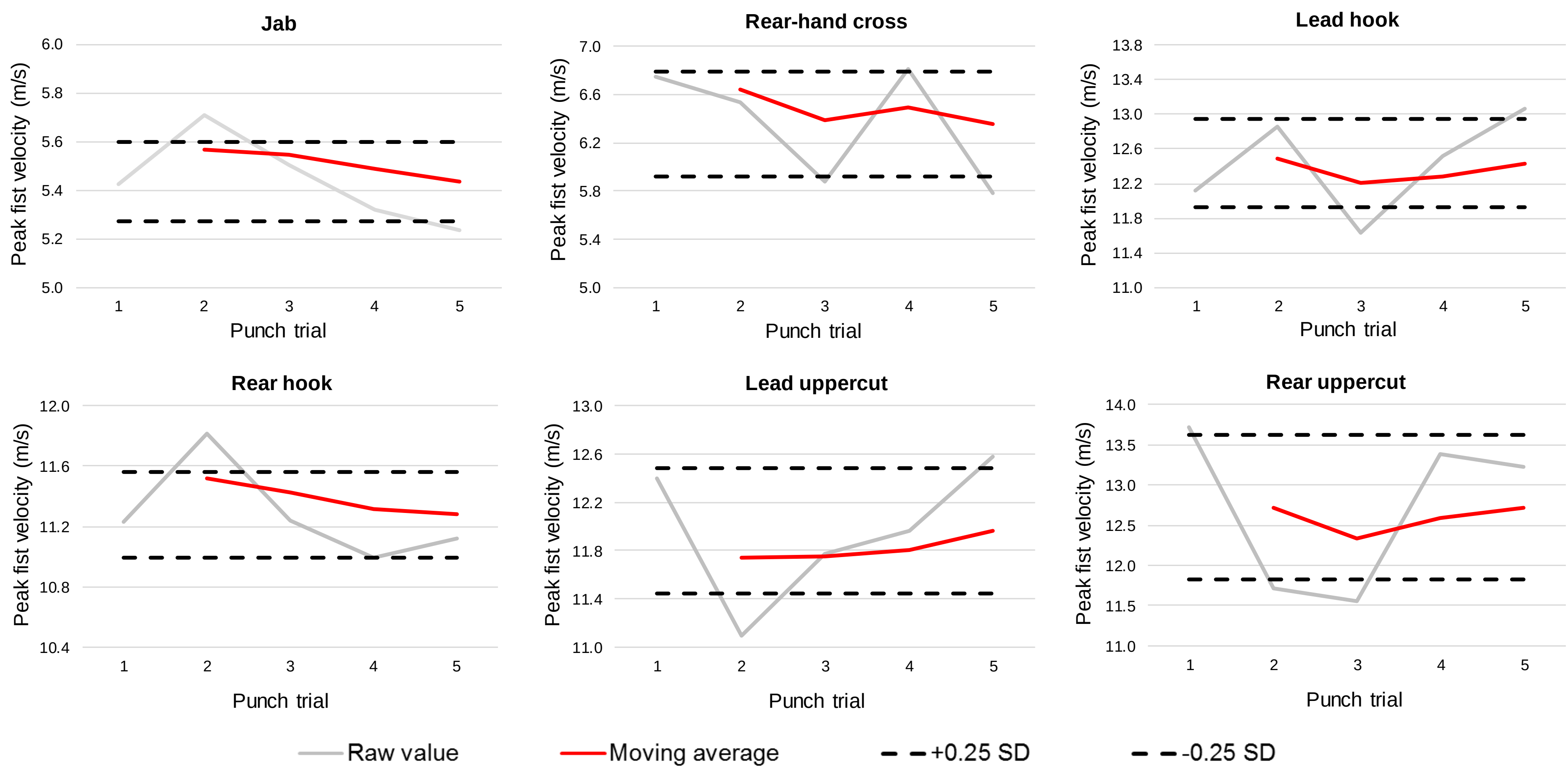

Figure 4.1. Example of sequential analysis of peak fist velocity of a randomly selected boxer.

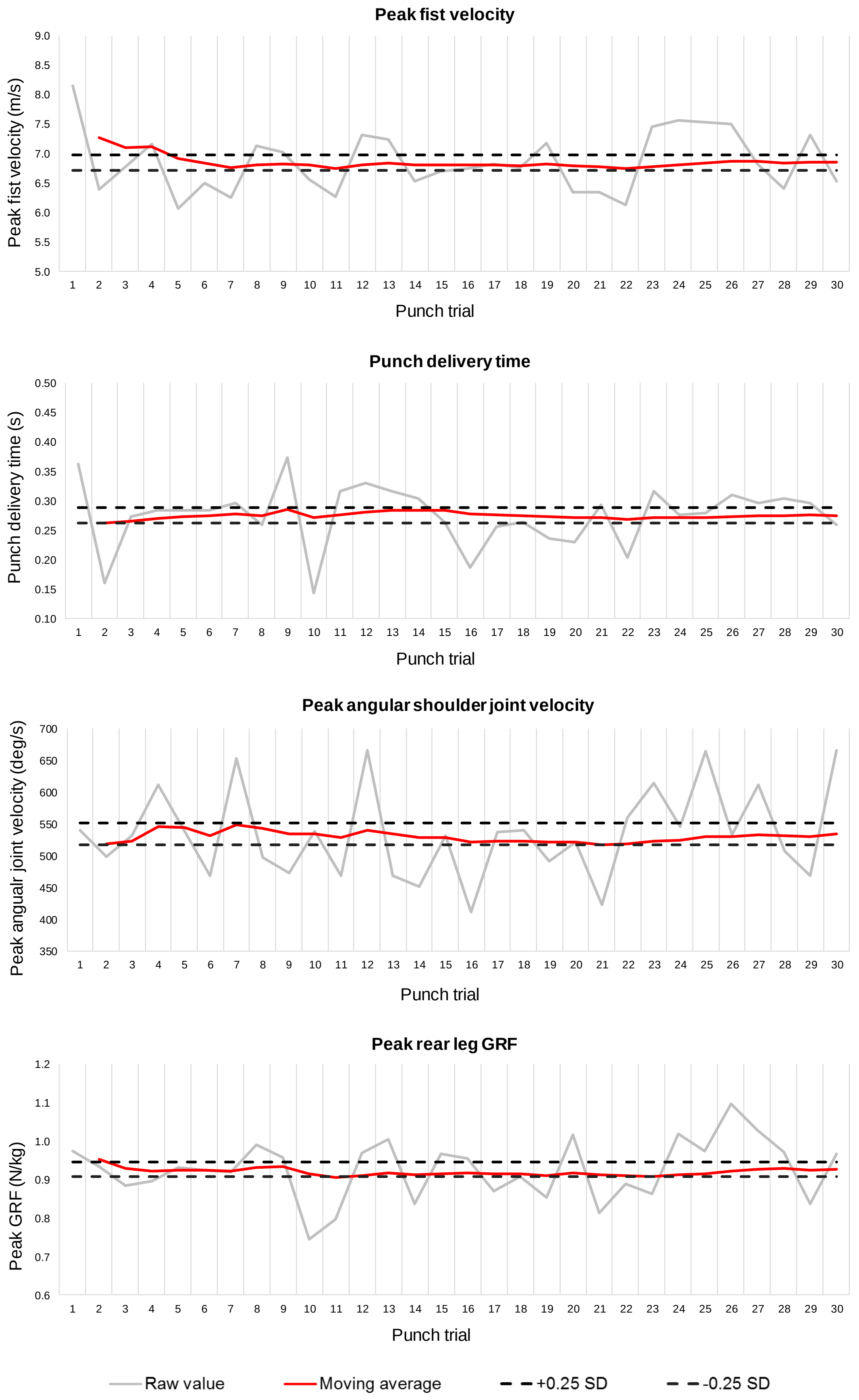

Figure 4.2. Example of sequential analysis of selected kinetic and kinematic variables in a 30-trial condition of a single boxer during rear-hand cross punches.

4.3. Results

4.3.1. Within-subject and biological variability

Within-subject variability was low-to-high (1.1-29.5%) (Table 4.1) across the six kinematic variables, though was only significantly different between punch types for delivery time ($P < 0.001$) and peak fist velocity ($P = 0.011$). The timing of peak elbow joint angular velocity differed between punches ($P < 0.001$), with biological variability ranging from 0.6 (rear-hand cross) to 5.7% (rear hook), after the standard error of means (SEM%) of approximately 2.6% (0.5-4.6%) were accounted for. For example, for delivery time, post-hoc analysis confirmed that rear-hand cross variability was significantly different to the lead hook ($P = 0.001$, $d = 1.2$), but not any other punch type ($P > 0.003$, $d = 0.3$-1.1).

For the six kinetic variables, only peak lead leg GRF CV% exhibited a significant difference between punch types ($P < 0.001$), likely owing to the jab's markedly greater variability compared to other punch types (especially the rear hook and lead uppercut) (Table 4.2). Indeed, the jab's biological variation (13.8%) was almost twice that of the rear-hand cross (7.6%) and three times that of the lead uppercut (5.1%). This was also mirrored in the within-subject and biological variation for lead leg vertical impulse, with the highest variability (jab) over twice that of the lowest (rear uppercut) (Table 4.2). For punch type comparisons, post-hoc analysis revealed that peak lead leg GRF variability for the jab was significantly greater than all other punch types ($P < 0.006$, $d = 1.2$-1.3), except for the rear-hand cross ($P = 0.11$, $d = 1.1$).

4.3.2. Between-subject variability and smallest worthwhile change (SWC%)

Between-subject variability was high (1.4-47.9%) across all punch types and all kinematic variables, with the jab exhibiting the greatest variation and SWC% for delivery time, the lead uppercut for peak fist velocity, and rear-hand cross for peak angular joint velocities (shoulder and elbow), respectively (see Tables 4.3 and 4.4). Meanwhile, the rear-hand cross exhibited the least variation for the timing of peak elbow joint angular velocity (SWC% = 0.1%), while the lead uppercut exhibited marginally higher SWC% for the shoulder joint (SWC% = 0.2%).

Between-subject variability was also high across each kinetic variable for each punch type, with peak lead leg GRF variation being greatest in the jab (38%) and rear leg GRF in the rear uppercut (34.9%), respectively (see Table 4.3). The rear uppercut also exhibited the largest SWC% for lead leg braking (18.3%) and rear leg propulsive (18.2%) impulses, while the jab demonstrated the largest vertical impulse SWC% for both lead (20.9%) and rear (14.6%) legs.

4.3.3. Relationship between years of boxing experience and within-subject variability of kinematic and kinetic variables.

No significant relationships were observed between years of experience and any biomechanical variable across punch types (Table 4.5). The highest positive associations were observed for peak rear leg GRF of the rear-hand cross ($r = 0.31$, $P > 0.05$) and peak lead leg GRF of the lead hook ($r = 0.30$, $P > 0.05$). Moderate negative associations were found for rear uppercut peak fist velocity ($r = -0.45$, $P > 0.05$) and lead uppercut peak elbow joint angular velocity ($r = -0.45$, $P > 0.05$).

Table 4.1. Within-subject and biological variability of kinematic variables across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	RHC	Lead hook	Rear hook	Lead uppercut	Rear uppercut	Jab	RHC	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Punch delivery time (ms)	18.8 ± 9	21.8 ± 8.1^{LH}	12.2 ± 4.1^{C}	17.3 ± 5.1	11.3 ± 5.2	13.4 ± 4.8	10.4 ± 5	12.0 ± 4.5^{LH}	6.7 ± 2.3^{C}	9.5 ± 2.9	6.3 ± 2.8	7.4 ± 2.6
Peak fist velocity (m/s)	14.3 ± 5.2	7.4 ± 2.1	8.7 ± 2	8.7 ± 2.6	19.8 ± 18.4	14.3 ± 9.4	7.9 ± 2.9	4.1 ± 1.2	4.8 ± 1.1	4.8 ± 1.4	9.8 ± 10.4	7.9 ± 5.2
Peak shoulder joint angular velocity (deg/s)	20.6 ± 13.1	29.3 ± 28.4	21.6 ± 13.8	21.2 ± 9.4	12.8 ± 6.5	14.4 ± 6.5	11.4 ± 7.2	16.2 ± 15.7	11.9 ± 7.6	11.7 ± 5.2	7.1 ± 3.6	8.0 ± 3.6
Peak elbow joint angular velocity (deg/s)	25.9 ± 21.8	26.7 ± 13.8	21.7 ± 7.9	25.5 ± 9	19.0 ± 5.3	29.5 ± 23.7	14.3 ± 12.1	14.8 ± 7.6	12.0 ± 4.4	14.1 ± 5	10.5 ± 2.9	16.3 ± 13.1
Timing of peak shoulder joint angular velocity (% of punch)	9.1 ± 7.7	6.4 ± 5.1	10.9 ± 9.2	4.7 ± 5.2	1.7 ± 2.8	5.3 ± 7.6	5.0 ± 4.2	3.6 ± 2.8	6.0 ± 5.1	2.6 ± 2.9	0.9 ± 1.6	2.9 ± 4.2
Timing of peak elbow joint angular velocity (% of punch)	1.8 ± 1.3	1.1 ± 0.6	6.8 ± 4.9	10.3 ± 7.4	6.6 ± 5.7	8.5 ± 8.1	1.0 ± 0.7	0.6 ± 0.4	3.8 ± 2.7	5.7 ± 4.1	3.6 ± 3.2	4.7 ± 4.5

Values presented as mean ± SD, RHC = rear-hand cross.

^{C} significantly different to the cross ($P < 0.003$).
^{LH} significantly different to the lead hook ($P < 0.003$).

Table 4.2. Within-subject and biological variability of kinetic variables across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	RHC	Lead hook	Rear hook	Lead uppercut	Rear uppercut	Jab	RHC	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Peak lead leg GRF (N/kg)	24.9 ± 11.7[LH,RH.LU]	13.7 ± 5.2	11.8 ± 4.7[J]	9.9 ± 3.3[J]	9.3 ± 3.7[J]	10.1 ± 6.0	13.8 ± 6.4[LH,RH.LU]	7.6 ± 2.9	6.5 ± 2.6[J]	5.5 ± 1.8[J]	5.1 ± 2[J]	5.6 ± 3.3
Peak rear leg GRF (N/kg)	12.6 ± 6.6	10.3 ± 4.9	17.1 ± 10.9	10.2 ± 5.3	11.9 ± 8.4	12.2 ± 4.5	7.0 ± 3.6	5.7 ± 2.7	9.5 ± 6	5.6 ± 2.9	6.6 ± 4.6	6.7 ± 2.5
Total lead leg net braking impulse (N/s/kg)	-81.9 ± 40.4	-34.8 ± 13.9	-60.1 ± 25.9	-26.1 ± 8.3	-36.0 ± 24.1	-22.6 ± 9.8	-43.9 ± 21.9	-19.2 ± 7.7	-29.9 ± 18.3	-14.4 ± 4.6	-19.9 ± 13.3	-12.5 ± 5.4
Total lead leg vertical impulse (N/s/kg)	52.2 ± 28.2	37.6 ± 15	27.2 ± 10.9	28.5 ± 9.3	24.9 ± 13.5	22.8 ± 6.6	28.8 ± 15.6	20.8 ± 8.3	15.0 ± 6	15.8 ± 5.1	13.8 ± 7.4	12.6 ± 3.7
Total rear leg net propulsive impulse (N/s/kg)	47.3 ± 23.7	47.0 ± 15.5	47.9 ± 27.1	34.6 ± 10.5	33.2 ± 19.5	29.9 ± 15.2	26.1 ± 13.1	26.0 ± 8.6	26.5 ± 15	19.1 ± 5.8	18.4 ± 10.8	16.6 ± 8.4
Total rear leg vertical impulse (N/s/kg)	39.0 ± 21.9	49.4 ± 15.4	29.9 ± 16	38.1 ± 11.6	25.6 ± 13.4	28.6 ± 13.9	21.6 ± 12.1	27.3 ± 8.5	16.5 ± 8.9	21.1 ± 6.4	14.2 ± 7.4	15.8 ± 7.7

Values presented as mean ± SD., RHC = rear-hand cross.

[J] significantly different to the jab ($P < 0.003$).
[LH] significantly different to the lead hook ($P < 0.003$).
[RH] significantly different to the rear hook ($P < 0.003$).
[LU] significantly different to the lead uppercut ($P < 0.003$).

Table 4.3. Between-subject variation (CV%) of kinetic and kinematic variables across punch techniques.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Punch delivery time (ms)	40.4	35.7	24.4	23.2	19.4	20.6
Peak fist velocity (m/s)	16.2	12.6	14.6	17.6	42.5	17.2
Peak shoulder angular velocity (deg/s)	24.1	40.4	22.4	26.3	13.0	12.3
Peak elbow angular velocity (deg/s)	37.0	47.9	36.2	47.9	27.9	34.8
Timing of peak shoulder angular velocity (% of punch)	11.9	11.5	15.5	6.6	3.3	8.5
Timing of peak elbow angular velocity (% of punch)	2.3	1.4	12.3	13.7	10.2	11.9
Peak lead leg GRF (N/kg)	38.0	34.3	28.6	25.0	27.8	27.5
Peak rear leg GRF (N/kg)	27.3	25.1	27.8	23.8	27.1	34.9
Lead leg net braking impulse (N/s/kg)	129.2	71.4	94.1	63.0	59.0	51.6
Lead leg vertical impulse (N/s/kg)	116.1	71.6	52.8	61.9	47.2	48.7
Rear leg net propulsive impulse (N/s/kg)	90.1	78.1	87.4	68.4	61.5	60.4
Rear leg vertical impulse (N/s/kg)	80.2	83.4	59.7	64.2	49.4	56.1

Note: Data presented as CV%

Table 4.4. Worthwhile change statistics for kinetic and kinematic variables across punch techniques.

	Jab			Rear-hand cross			Lead hook			Rear hook			Lead uppercut			Rear uppercut		
	SWC %	MWC %	LWC %	SWC %	MWC %	LWC %	SWC %	MWC %	LWC %	SWC %	MWC %	LWC %	SWC %	MWC %	LWC %	SWC %	MWC %	LWC %
DT	7.4	22.2	44.4	6.0	18.1	36.2	4.4	13.3	26.5	3.3	9.8	19.6	3.3	9.9	19.7	3.3	10.0	19.9
FV	2.9	8.7	17.4	2.5	7.4	14.9	3.1	9.2	18.4	3.3	10.0	19.9	4.3	13.0	26.0	3.0	9.0	17.9
SJAV	3.9	11.8	23.5	7.8	23.3	46.6	3.4	10.1	20.3	4.8	14.4	28.8	2.3	6.9	13.7	2.0	5.9	11.7
EJAV	7.0	21.1	42.2	8.6	25.8	51.6	6.9	20.8	41.6	8.1	24.4	48.8	5.2	15.7	31.3	5.2	15.6	31.1
SJAV%	1.5	4.5	9.0	1.7	5.1	10.2	2.6	7.9	15.8	0.4	1.2	2.4	0.2	0.6	1.1	0.3	0.8	1.6
EJAV%	0.3	1.0	1.9	0.1	0.4	0.7	2.6	7.8	15.5	2.5	7.5	15.1	1.4	4.2	8.4	1.8	5.3	10.6
LLGRF	6.5	19.6	39.1	6.5	19.5	39.1	5.4	16.3	32.6	4.8	14.5	29.0	5.4	16.2	32.5	5.2	15.7	31.3
RLGRF	5.0	15.0	30.0	4.6	13.9	27.9	4.8	14.5	28.9	4.5	13.6	27.2	5.0	15.0	30.1	6.8	20.4	40.8
LLFyI	15.9	47.6	95.2	13.0	39.0	78.0	16.2	48.7	97.4	11.3	33.9	67.8	10.3	30.9	61.8	18.3	55.0	110.1
LLFzI	20.9	62.8	125.6	12.8	38.4	76.7	9.3	28.0	56.0	10.4	31.1	62.3	8.1	24.4	48.8	9.1	27.4	54.7
RLFyI	16.0	47.9	95.9	13.7	41.1	82.2	15.6	46.7	93.3	12.3	36.9	73.9	11.2	33.7	67.5	18.2	54.6	109.3
RLFzI	14.6	43.7	87.5	14.3	43.0	86.0	10.9	32.8	65.6	11.1	33.2	66.5	9.0	27.1	54.3	10.0	29.9	59.7

SWC% = small worthwhile change, MWC% = moderate worthwhile change, LWC% = large worthwhile change, DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse

Table 4.5. Pearson correlations (± 95% CI) between boxing experience (years) and within-subject variability of kinetic and kinematic variables.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
DT	0.05 (-0.54 to 0.64)	-0.19 (-0.78 to 0.39)	-0.04 (-0.64 to 0.55)	0.11 (-0.48 to 0.70)	0.06 (-0.53 to 0.65)	-0.14 (-0.74 to 0.44)
FV	-0.21 (-0.79 to 0.37)	-0.01 (-0.61 to 0.58)	-0.18 (-0.77 to 0.40)	-0.29 (-0.86 to 0.28)	-0.32 (-0.89 to 0.24)	-0.45 (-0.99 to 0.07)
SJAV	0.27 (-0.29 to 0.85)	0.12 (-0.47 to 0.71)	-0.29 (-0.86 to 0.27)	0.10 (-0.48 to 0.70)	-0.10 (-0.70 to 0.49)	-0.39 (-0.94 to 0.15)
EJAV	-0.07 (-0.67 to 0.52)	0.17 (-0.41 to 0.76)	0.14 (-0.45 to 0.73)	0.20 (-0.38 to 0.79)	-0.45 (-0.99 to 0.07)	0.15 (-0.43 to 0.74)
SJAV%	-0.04 (-0.64 to 0.55)	-0.30 (-0.87 to 0.26)	-0.45 (-0.98 to 0.08)	-0.44 (-0.98 to 0.08)	-0.11 (-0.71 to 0.47)	-0.23 (-0.82 to 0.34)
EJAV%	-0.34 (-0.90 to 0.22)	0.11 (-0.48 to 0.71)	-0.31 (-0.88 to 0.25)	-0.02 (-0.62 to 0.57)	-0.22 (-0.80 to 0.36)	0.11 (-0.47 to 0.71)
LLGRF	-0.04 (-0.64 to 0.55)	0.24 (-0.33 to 0.82)	0.30 (-0.27 to 0.87)	-0.27 (-0.84 to 0.30)	-0.02 (-0.62 to 0.57)	0.05 (-0.54 to 0.65)
RLGRF	0.10 (-0.49 to 0.69)	0.31 (-0.25 to 0.88)	0.02 (-0.57 to 0.62)	-0.22 (-0.81 to 0.35)	0.08 (-0.51 to 0.67)	-0.36 (-0.92 to 0.18)
LLFyI	0.18 (-0.40 - 0.77)	0.11 (-0.48 to 0.70)	-0.14 (-0.73 to 0.44)	-0.35 (-0.91 to 0.20)	0.13 (-0.45 to 0.73)	-0.09 (-0.69 to 0.50)
LLFzI	-0.13 (-0.72 to 0.45)	-0.25 (-0.83 to 0.32)	-0.03 (-0.63 to 0.56)	0.34 (-0.21 to 0.91)	-0.02 (-0.62 to 0.57)	0.14 (-0.44 to 0.73)
RLFyI	0.003 (-0.59 to 0.60)	-0.14 (-0.73 to 0.45)	-0.26 (-0.84 to 0.31)	-0.06 (-0.65 to 0.53)	-0.10 (-0.70 to 0.49)	0.03 (-0.55 to 0.63)
RLFzI	0.07 (-0.52 to 0.67)	-0.14 (-0.74 to 0.44)	-0.02 (-0.62 to 0.57)	-0.07 (-0.67 to 0.52)	-0.02 (-0.61 to 0.57)	0.06 (-0.53 to 0.66)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse

4.4. Discussion

This study has revealed considerable within- and between-subject variability across the majority of the kinetic and kinematic variables measured for all punch types. Interestingly, such variability was independent of the amount of boxing experience (years). Though certain kinematic variables exhibited comparable degrees of variance (i.e. delivery time and peak fist velocity), high differences in MV across punch type for angular joint velocity and kinetic variables highlight MV as being characteristic of maximal punching, with boxers appearing to manipulate biomechanical variables via different coordination strategies in order to achieve a relatively consistent intensity and end-product. Coaches and boxers should therefore acknowledge the existence and magnitude of MV, be mindful of its influence on maximal punching, and recognise how different punches exhibit changeable degrees of kinetic and kinematic variance.

4.4.1. Within-subject variation

Compensatory joint actions and subsequent movement inconsistencies resulting from ballistic, complex actions may assist in explaining the moderate-to-large within-subject variation of the jab, rear-hand cross, and lead hook observed in the current study. It is likely that such compensatory movements (i.e. intentional differences in coordination at the shoulder and elbow joints) ensure peak fist velocity (and, perhaps, punch delivery time) is comparatively consistent. This notion that outcome consistency of motion does not necessarily require movement consistency (Bartlett et al., 2007), is supported by findings from other sports that suggest the occurrence of such adaptations in the execution of sport-specific skill is indicative of high-level performance (Bartlett, 2007; Hanford, 2006; Handford et al., 1997; Scott et al., 1997; Wagner et al., 2012). In this way, MV is seen as a ‘functional’ way of interacting and adapting to changing sporting conditions (Langdown et al., 2012) and is symptomatic of an ability that allows performers to adapt to the ever-changing stimuli comprising dynamic sporting environments (Bartlett et al., 2007; Bradshaw et al., 2009; Davids, Lees, & Burwitz, 2000; Williams, Davids, & Williams, 1999).

Though all punches exhibited ‘high’ variability, it was notable the second most commonly performed punch within competition (after the jab), the rear-hand cross (Davis et al., 2013; 2015; 2018; Slimani et al., 2017; Thomson & Lamb, 2016), displayed the highest within-subject and biological variance. The large MV may relate to the rate at which this punch is delivered, with its shorter delivery times than hooks and uppercuts, respectively (Chapter 3; Piorkowski et al., 2011). Indeed, previous research has reported how rapid and accelerative phases of motion, particularly during complex movements performed at high-speed, increase the likelihood of MV occurring as performers compensate for the ballistic nature of the action at distal joints segments (Darling & Cooke, 1987; van den Tillaar & Ettema, 2006; Wagner et al., 2012). However, this degree of MV by the rear-hand cross was surprising given it is considered less complex than hooks and uppercuts (comprising elbow extension and shoulder protraction predominantly; Hickey, 2006; Piorkowski et al., 2011) and is likely to be rehearsed more than other punch types (Davis et al., 2015; Slimani et al., 2017; Thomson, & Lamb, 2016).

Although the need for performers to demonstrate repeatable movement patterns is essential for optimising technique, possessing the ability to vary movement according to the competitive and environmental conditions of competition is also an important aspect of successful sports performance (Langdown et al., 2012). Furthermore, by intentionally minimising variability, and therefore constraining movement, performance could be negatively affected in that they may struggle to adapt to the conditions of competition (Langdown et al., 2012). Consequently, the high MV observed for peak shoulder and elbow joint angular velocities, particularly for the rear-hand cross (shoulder) and rear uppercut (elbow), may not be detrimental to performance given the intricate movement patterns that comprise punching technique(s). Indeed, previous research among sprinters has reported average angular joint velocity within-subject variation of 45.6 ± 22.6% (hip), 25.8 ± 17.8% (knee), and 27.8 ± 13.4% (ankle) for the stride leg (Bradshaw et al., 2007), reflecting how ‘large’ variations for certain kinematic variables may be dependent on individual structural, functional, and task constraints (McGarry et al., 2013), and may not negatively affect performance. However, further research pertaining to the MV of maximal punching is required in order to gain a better understanding of how much joint movement (particularly at the shoulder and elbow) is associated with optimal punching performance.

Further evidence supporting the existence (and possible desirability) of considerable MV even among the most prevalent (practiced) punches was seen for the peak lead leg GRF of the jab, which exceeded that of both the hooks and uppercuts. In principle, such a well-rehearsed punch ought to demonstrate the lowest MV across punch trials (Bartlett, 2007), but it seems not to be the case. Again, perhaps jab MV is directly influenced by boxing style and/or technique; offensive-minded boxers being more likely to use it as an attacking mechanism to cause damage and create openings for more forceful strikes (Haislet, 1968; Hickey, 2006), whereas defensive-minded and/or ‘counter-punching’ boxers prefer using it to keep an opponent at ‘long range’. As such, offensive-minded boxers may be accustomed to executing the jab at maximal intensity, while the defensive-minded boxers may not due to their differing strategies/style. Therefore, whilst all the current boxers were instructed to perform all trials for each punch type at maximal intensity (‘to throw knock-out punches whilst maintaining correct technique’), it is possible such differences were responsible for the variance in the lead leg GRF generated from the jab.

In general, the within-subject variance for peak GRF was lower than that observed for peak shoulder and elbow joint angular velocities, respectively. Though it is not apparent why this difference occurred, previous research has determined certain characteristics of dynamic movement require stability in order to optimise performance, whilst others necessitate varying degrees of variability in order to achieve successful outcomes (Handford, 2006; Yang et al., 2018). That is, by allowing certain features of movement to vary, biomechanical characteristics may be enhanced facilitating efficient compensatory movement(s) (Bartlett et al., 2007; Handford, 2006; Langdown et al., 2012). Indeed, in other dynamic sporting movements sharing similar kinematics to punching, GRF produced by the lead and rear legs has been shown to provide a stable base from which to generate force that can be transmitted distally to the hand/fist segment, generating high upper-limb velocities (Bartonietz, 1994; MacWilliams, Choi, Perezous, Chao, & MacFarland, 1998; McCoy, Gregor, Whiting, & Rich, 1984; McNally, Borstad, Oñate, & Chaudhari, 2015). Therefore, it is plausible the rigidity and stability afforded by lead and rear leg GRF during a maximal punch may facilitate degrees of functional MV at the shoulder and elbow joints that foster the transmission of force from the lower limbs to the fist via the kinetic chain (Cheraghi et al., 2014).

In contrast to peak GRF, lead and rear leg impulse (net braking/propulsive and vertical) exhibited the highest variability (within-subject, between-subject, and biological) of all variables. While such net braking impulse MV is markedly greater than values reported in studies examining sprint acceleration in team sport athletes (23.1%; Kawamori, Nosaka, & Newton, 2013) and track and field and team-sport athletes combined (14%; Hunter, Marshall, & McNair, 2005), it is difficult to explain. This large variation (particularly compared to peak GRF) among boxers likely relates to the time element inherent in the calculation of impulse. Indeed, peak GRF is dependent on an athlete's body mass and degree of force(s) exerted, and not time, whereas impulse is related to the total time taken to apply such forces (Moir, 2016). Therefore, the boxers may have produced comparatively consistent peak GRF across punch types, but applied these forces over varying time periods from punch initiation to the point of contact. In addition, another explanation may relate to lower-limb joint kinematics associated with maximal punches. In sprinting, lower-limb propulsive impulse was associated with high hip extension velocities (R^2 = 0.57) accounting for 57% of variance in peak sprint velocity, with greater magnitudes of lower-limb propulsion deemed necessary to achieve high peak accelerations (Hunter et al., 2005). In relation to punching, the ballistic nature of complex dynamic motions performed at high velocities (such as maximal punches) increases the probability of athletes compensating for such rapid motions through the variation of timings and magnitudes of distal joint kinematics (e.g. ankle joint angles, angular extension velocities and extensor moments) and associated muscular contractions (Wagner et al., 2012). Indeed, it is suggested that the rapid weight transfer from the rear leg to the lead leg (Turner et al., 2011), in addition to the rotational characteristics of maximal punching (Cabral et al., 2010) challenges the stability of boxers (Yoon & Kim, 2019), and in particular, those of less ability (Leal & Spaniol, 2016). This may encourage excessive motions/movements that results in less repeatable punch performances. Thus, it seems plausible to suggest that lower-limb joint kinematics and moments, diverse ranges of time spent applying force, and the dynamic nature of maximal punching may help to explain the large impulse variability in the current study.

4.4.2. Between-subject variation

All punch types exhibited large between-subject variation for punch delivery time and peak fist velocity, the largest for the jab (delivery time) and lead uppercut (peak fist velocity). This is consistent with the degree of within-subject variability referred to above for jab delivery time, and can be explained in the same manner (relating to fundamental technical, physical, and anthropometric differences between boxers; Guidetti et al., 2002; Khanna & Manna, 2006). However, the case for peak fist velocity of the lead uppercut is different. For example, the way in which boxers execute the frequently used jab within training/competition (e.g. as a ‘set up’ strike for more forceful punches, such as a rear-hand cross, or as a defensive punch to keep an opponent at a distance), plausibly magnifies between-boxer discrepancies. Moreover, the rapid and ballistic nature of the jab may also contribute to the degree of inter-boxer MV, with dynamic full-body movements performed at high-velocities often requiring distal joint segments to compensate for any superfluous movement variance in proximal segments (Darling & Cooke, 1987; van den Tillaar & Ettema, 2006; Wagner et al., 2012). It is also likely that these distal joint segment compensations explain the high between-subject variability of peak fist velocity during the lead uppercut. Though as the lead uppercut is the least executed punch type within competition, regardless of ability level (Davis et al. 2017; Kapo et al., 2008; Thomson & Lamb, 2016), the large (relative) inter-subject peak fist velocity variability observed might reflect the levels of technical expertise ('ability') of the boxers in the current study that could be independent of experience level.

Large between-subject variation in shoulder and elbow joint angular velocities was observed for all punch types, but particularly for the rear-hand cross (both joints) and rear hook (elbow). Although not directly comparable, Lenetsky et al. (2017) reported 'moderate' variability for the impact kinetics of rear-hand cross (9.3%) and rear hook (7.7%). Arguably, in their study and the current one, the levels of MV reported for these two punches have been influenced by the varying degrees of GRF and impulse generated by the boxers at the initiation of these punch types, resulting from mechanisms responsible for the generation of such force (such as lower-limb joint extension angles, extension velocities and extensor moments – Chapter 3). That is, based on the role of GRF, impulse, joint moments and lower-limb joint kinematics to distal joint segment velocities during punching (Chapter 3; Cheraghi et al., 2014, Lenetsky et al., 2013; Turner et al., 2011) and other ballistic movements (MacWilliams et al., 1998; McNally et al., 2015; Williams, 2012), there is further evidence of the occurrence of compensatory patterns of movement. Such patterns may also explain why lead and rear leg impulse (net braking/propulsive and vertical) exhibited the highest amount of between-subject variation; technical, muscle activity and/or lower-limb kinematic variability changes/adaptations between punch trials could have occurred to accommodate for large impulse and/or GRF values generated. To validate this theory, a future investigation to examine the link between lower-limb impulse, joint moments, and joint kinematics (e.g. extension angles and angular velocities) variability and electromyographic (EMG) analysis of punch types is warranted. Nonetheless, coaches should take note of the high MV across boxers and acknowledge that this may actually be a positive characteristic of punching technique and indicative of skilled performance (i.e. athletes intentionally modifying their technique in order to adapt to environmental and/or competitive situations; Bartlett, 2007; Button et al., 2003; Hanford, 2006; Wagner et al., 2012).

4.4.3. Smallest worthwhile change (SWC%)

The SWC% data presented herein suggest that certain kinetic and kinematic variables require lower increases than others to reflect a ‘meaningful’ change in maximal punch performance. Indeed, these novel findings imply that the upper-body kinematics of uppercut punches may not require the same magnitude of change as other punch types to be confident of a positive effect on performance. This was also the case for peak lead and rear leg GRF of hook punches, and lead and rear leg impulse of the rear hook and lead uppercut, respectively. Furthermore, the low SWC% for timings of peak angular joint velocities (shoulder and elbow) and peak fist velocity across all punches suggest that the increases needed to produce ’genuine’ differences in performance vary from punch-to-punch and variable-to-variable. Previous research across other sports has reported that performance increases of 0.3-1.5% will result in ‘meaningful’ improvements in track and field competitors (Peltola, 2005) and triathletes (Paton & Hopkins, 2005), respectively. Unfortunately, no previous literature has examined SWC% in relation to boxing and/or punching performance. However, it is apparent that the large biomechanical MV reported in the current study, and subsequent SWC% values, suggest the kinetics and kinematics of maximal punching require substantial changes to have a ‘meaningful’ impact on technique compared to other sporting movements/techniques.

Indeed, given the high within- and between subject variability across all punch types for the majority of maximal punch kinetic and kinematic measures, it appears that performance changes resulting from training interventions would have to be 'large' in order to exhibit 'meaningful' changes from baseline measures. More specifically, biomechanical measures with larger MV across punch types (e.g. impulse) will require larger changes than variables exhibiting smaller MV (e.g. delivery time) following a training intervention. Though future research is required to replicate these findings, being able to monitor changes in maximal punch performance following training interventions would seem to be a valuable tool for coaches and boxers to be confident of genuine change in technique. This could provide useful information for coaches and boxers as to the influence of training interventions to specific measures related to maximal punching, which may assist in monitoring the magnitude of kinetic and kinematic performance changes. Therefore, future research should investigate the effects of different training interventions on maximal punching performance, and quantify if such interventions produce 'meaningful' performance changes on maximal punch kinetics and kinematics.

4.4.4. Effect of boxing experience on within-subject variability of kinematic and kinetic variables.

A curious finding was that years of boxing experience was not associated with the MV of the kinematic or kinetic variables across punch types; maximal effort punching is underpinned by high variability regardless of experience. On the basis of previous research examining ballistic actions, it was expected the more experienced the boxer, the lesser the MV would be exhibited (Bradshaw et al., 2007; 2009; Fleisig et al., 2009;

Lenetsky et al., 2017). Accordingly, the current study's findings support the notion that MV is symptomatic of skilled performers who modify the execution of movement-based skills in order to adapt to the task in hand (Bartlett, 2007; Button et al., 2003; Hanford, 2006; Wagner et al., 2012), particularly during striking actions within combat sports (Orth et al., 2018). Even though the trials could be considered somewhat closed environments, the ballistic and complex nature of punching still requires the ability to adapt features of technique, and this is clearly supported in the data.

Of further note were the small negative associations (albeit non-significant) of experience with peak fist velocity of all punch types. In effect, the more experienced the boxer, the lower the MV for this variable. In handball, Wagner et al. (2012) found that players across all ability levels compensated for an increase in joint velocity during the acceleration phase of a handball throw, yet the more experienced/skilled performers exhibited better 'control' (i.e. accuracy of high-velocity throws) during this process. Other research has also reported how skilled throwers manipulate ball release velocity in order to achieve greater outcome consistency (Button et al., 2003; Kudo et al., 2000). Though accuracy was not quantified in the current study, that boxers were given the instruction to execute knock-out punches, it is possible that the negative associations are reflective of MV compensations made by the more experienced/skilled boxers. That is, the less experienced and/or skilled boxers focussed on 'fast' punches, and thereby achieved greater fist velocities across trials, whereas the more experienced and/or skilled performers sacrificed measures of fist velocity in favour of delivering more forceful punches (Joch et al., 1981; Leal & Spaniol, 2016; Smith et al., 2000). Importantly this analysis has highlighted that coaches and boxers should be made aware that experience has no impact on maximal punch MV, with boxers of all experience levels exhibiting comparable MV. This suggests that perhaps individual punching technique, fighting ‘style’ and/or anatomical factors (e.g. limb-length) may have a larger influence on MV than experience, though this was beyond the scope of the current study and is recommended as an area for future research.

4.4.5. Conclusion

In quantifying the MV of kinematic and kinetic variables that comprise maximal punches performed by amateur boxers, the current study has found that: (i) maximal punching kinematics and kinetics exhibit high within-subject variability in comparison to other sporting movements; (ii) high between-subject variability is also a feature of the kinetic and kinematic variables associated with maximal punching, and (iii) no relationships exist between within-subject variability of maximal punch kinematic and kinetic variables and years of boxing experience. While these findings advance our understanding of the movement variance of maximal punches and its association with boxing experience, future research pertaining to the independent influence of a boxer’s physical qualities on punch kinetics and kinematics is justified.

Chapter 5

An analysis of selected physical performance-related determinants of maximal punching performance among experienced amateur boxers

Abstract

The purpose of this study was to quantify the relationships between measures of strength, power, speed and three-dimensional (3D) kinetics and kinematics of punching techniques characteristic of boxing (jab, rear-hand cross, lead and rear hook, lead and rear uppercut). Fourteen male amateur boxers (age: 25.9 ± 4.2 years, stature: 180 ± 6.3 cm, body mass: 78.8 ± 12 kg, years of experience: 7.4 ± 2.9 years) performed physical assessments (back squat 1RM, bench press 1RM, jump squat (30% back squat 1RM), bench throw (30% bench press 1RM), med-ball shot put (4 kg), 20 m sprint) that were found to correlate with 3D kinematic and kinetic data for each punch type. Back squat 1RM exhibited very large relationships with jab, rear-hand cross and lead hook peak fist velocities (r = 0.70-0.74), and moderate associations with rear hook and lead and rear uppercut peak fist velocities (r = 0.41-0.47), respectively. Bench press 1RM correlated with rear-hand cross, lead hook and rear uppercut peak fist velocities (r = 0.51-0.60). Moderate associations between jump squat maximum power and peak lead and rear leg GRF for the rear uppercut were observed (r = 0.30-0.38), while bench throw maximum power moderately correlated (r = 0.32-0.60) with angular shoulder and elbow velocities across all lead hand punches (jab, lead hook, and lead uppercut). Rear hand shot put distance correlated with peak lead leg GRF and speed (10 and 20 m sprint performance) with peak rear leg GRF (r = 0.58-0.65), respectively, across all rear hand punches (cross, hook, and uppercut). These findings advance the understanding of how physical qualities relate to biomechanical variables of punching. Future research should investigate if enhancing specific physical characteristics through strength and conditioning strategies improve the kinetic and kinematic characteristics of maximal punching.

Key words: combat sports, boxing, punching, muscular strength, muscular power.

Given the identification of maximal punch biomechanics (Chapter 3) and the MV associated with these qualities (Chapter 4), research is required to quantify the associations between maximal punch biomechanics and physical performance-related qualities. This study will therefore investigate such relationships to identify if physical performance-related qualities influence biomechanical variables are associated with maximal punching.

5.1. Introduction

The fundamental striking techniques in boxing comprise straight, hook and uppercut punches with each technique requiring a synergistic, coordinated recruitment of leg, trunk and arm musculature (Turner et al., 2011). The intention during competition is to out-perform or knock-out an opponent through the implementation of 'clean' punching techniques. Bouts are scored based upon the number of 'quality' blows landed to the target areas (head and torso), domination via technical and tactical superiority and competitiveness of each boxer (AIBA, 2017a). In order to cause discomfort to an opponent, and potentially, score a knock-out (the most desired outcome to a contest, Mack et al., 2010), a boxer must possess a multitude of physical qualities that work synergistically to create a punch that is delivered with considerable force and velocity (Loturco et al., 2016).

An examination of amateur boxing competition reveals successful performance requires a boxer to possess a range of physical qualities, particularly the ability to punch at maximal intensity across the duration of a contest. More specifically, alongside the importance of technique, maximal punching necessitates an array of physical characteristics that must be augmented if punching performance is to be optimised (Chaabene et al., 2015). Understanding the specific components that influence a maximal punch will educate boxers and coaches about which physical attributes should be trained during contest preparation (Loturco et al., 2016). Previous research has reported that muscular power and fist velocity are the most critical components of successful striking in combat sports in relation to landing a clean, forceful strike before an opponent has a chance to defend, evade or counter (Chang et al., 2011). Additionally, the importance of muscular strength in the upper and lower limbs to the execution of maximal punching has been promoted (Chaabene et al., 2015; Del Vecchio et al., 2019) with the inference being a boxer will struggle to achieve high impact forces (and potentially, high peak fist velocities) based on the linear relationship between force and power production (Cormie et al., 2011a) - without possessing a degree of relative strength (Cormie et al., 2011b). Indeed, muscular strength has been shown to influence force-time characteristics (e.g. rate of force development, neuromuscular power, limb acceleration) which can be effectively transferred to dynamic athletic activities (Suchomel et al., 2016; 2018).

Although previous research has examined physical and physiological demands of boxing training and competition (Chaabene et al., 2015; Del Vecchio, 2011; Guidetti et al., 2002; Smith, 2006), few studies have accurately quantified the physical and/or physiological correlates of maximal punches. Attempts have been made to determine the importance of isometric muscular strength (Guidetti et al., 2002; Khanna & Manna, 2006; Loturco et al., 2014; Ramírez García et al., 2010) to punching performance, with associations reported between upper- and lower-body isometric force production and the punching forces of maximal jab (r = 0.68-0.69) and rear-hand cross (r = 0.73-0.83) punches among elite amateur boxers (Loturco et al., 2016). However, the limited movement specificity and disparate motor unit activation patterns between isometric and dynamic/explosive actions means velocity-based measures of performance (e.g. joint velocities) tend not to be associated with isometric strength measures (Wilson et al., 1995). Indeed, isometric force (*r* = 0.47-0.55) and RFD (*r* = 0.08-0.31) assessments have previously exhibited poor relationships with dynamic, high-velocity upper-body performance (Murphy & Wilson, 1996). Consequently, as the use of dynamic assessments is likely superior to isometric tests in the physical assessment of athletes involved in sports comprising high-velocity actions (Tanner & Gore, 2013), establishing the associations between physical performance-related traits and biomechanical characteristics that influence maximal punching via a range of dynamic tests is warranted to verify the role of specific physical traits to specific punch types.

Though dynamic assessments, such as unloaded jumps (Del Vecchio et al., 2017; 2019; Pilewska et al., 2017), bench presses (Kim et al., 2018), and medicine ball shot puts (Obmiński et al., 2011), have been used in previous research to establish relationships with straight punches (jab and rear-hand cross), the influence of strength and power measures to hook and uppercut punches remains notably absent. Therefore, a comprehensive appraisal of all fundamental punching techniques and physical traits purported to influence maximal punching is necessary to establish how these traits influence the biomechanical characteristics of all punch types. Additionally, previous research concerning strength and power variables and their relationship with boxing punches have only focussed upon the associations with punch impact force (Loturco et al., 2016; Pilewska et al., 2017) and power (Del Vecchio et al., 2017; 2019), whilst the association between strength and power and other key biomechanical variables of maximal punching, such as fist velocity, upper-limb joint velocities and GRF, has not been investigated. As these variables are critical to the execution of maximal punches (Chapter 3; Piorkowski et al., 2011) and have even been shown to influence the degree of impact forces generated during a maximal punch (Mack et al., 2010), establishing their relationship with physical performance-related qualities will provide coaches and boxers with a comprehensive understanding of how punch performance can be augmented. Furthermore, relationships between punch kinetics and kinematics and additional physical components that may influence maximal punching, such as limb acceleration (Adamczyk & Antoniak, 2010, Tanner & Gore, 2013) and full-body power (Lenetsky et al., 2013; Turner et al., 2011) are lacking in the boxing literature. Therefore, the quantification of physical performance-related variables that are imperative to punching performance via dynamic assessments could provide an improved representation of the influence specific physical qualities have on maximal punching performance.

Recognising training methods that could enhance maximal punching is desirable to prepare boxers for the demands of competition and to optimise contest preparation (Loturco et al., 2016; Piorkowski et al., 2011). Quantifying traits that influence maximal punching could be achieved through a combination of physical assessments and biomechanical punch analyses. Contemporary research has attempted to verify the role of specific physical qualities and/or training methods to maximal punching (Kim et al., 2018). However, due to the different methods recommended by authors to improve punching performance, boxers and coaches have often depended on 'time-honoured' approaches to training (Bourne et al., 2002), including Olympic lifts (OL) and barbell/dumbbell lifts (Lenetsky et al., 2013; Ruddock et al., 2016; Turner et al., 2011), weighted plyometrics (PT) (Bružas et al., 2016), and punching against elastic resistance (Markovic et al., 2016) or weighted resistance (Matthews & Comfort, 2008). Increasing the knowledge and understanding of this area could foster the development of training practice and punch-specific RT interventions with the aim of augmenting key kinetic and kinematic variables associated with the fundamental punch techniques observed. The aim of this study therefore was to quantify the relationships between kinetic and kinematic characteristics of maximal punches with particular measures reflecting muscular strength, power and speed.

5.2. Methods

5.2.1. Participants

Fourteen males (age: 25.9 ± 4.2 years, stature: 179.9 ± 6.3 cm, body mass: 78.8 ± 12 kg, years of experience: 7.4 ± 2.9 years) across six weight categories (light-welterweight (60-64 kg) to super-heavyweight (91+ kg)) were recruited from six amateur boxing clubs located across the North West of England, based upon current boxing experience (≥ 2 years) and official bout history (≥ 2 bouts). A sample size calculation (G*Power version 3.1.9.4, Universität Düsseldorf, Dusseldorf, Germany - Faul et al., 2009) with relevant input parameters (α level = 0.05, power = 0.8) and effect size (0.67 for strength and power performance variables) based upon Loturco et al. (2016), produced a sample of 12 (Appendix 1). All participants provided written informed consent prior to the study and institutional ethical approval was granted by the Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee.

5.2.2. Design

The study adopted a cross-sectional, within-subjects design to quantify the associations between kinetic and kinematic aspects of six maximal punches (jab, rear-hand cross, lead and rear hook, lead and rear uppercut) and performance across selected physical assessments deemed to be influential to maximal punching

(Adamczyk et al., 2010; Chang et al., 2011; Lenetsky et al., 2013; Loturco et al., 2016). All physical performance-related data were collected in one session and participants did not require separate familiarisation trials for either biomechanical or physical assessment procedures as all had prior experience (≥ 2 years) of performing the punch techniques used in the present study and demonstrated competency for the required movement patterns (squat and upper-body horizontal push).

5.2.3. Procedures

Biomechanical assessment of punch trials were completed ≤ 30 days prior to the physical assessments as part of a previous study (Chapter 3), with the acquired data from the kinetic and kinematic variables (Table 5.1) used to quantify the relationships with physical performance-related variables. Physical assessments were completed over a single ~180-minute session with participants advised not to exercise intensely 24 hours prior to the assessment day (Harman, 2016). The order of assessments was as follows: back squat 1RM, bench press 1RM, jump squat, bench throw, medicine ball shot put (left and right arms with a 4 kg medicine ball) and 20 m sprint (with times also recorded at the 10 m interval) (see Figure 5.1). In line with previous research, the order of the physical assessments addressed muscular strength

followed by muscular power and sprint speed, respectively (Coulson & Archer, 2015; Haff & Triplett, 2016; Tanner & Gore, 2013). Each assessment was separated by a 5-minute rest period to facilitate maximum recovery between tests (de Salles et al., 2009; Haff & Triplett, 2016). Maximal power (Pmax) was recorded for each bench throw and jump squat trial via a linear transducer (GymAware optical encoder, Kinetic Performance Technology, Canberra, Australia), while 10 and 20 m sprint times were measured via single-beam timing gates (Brower TC-System, Brower Timing Systems, Utah, USA) set at consistent heights (1 m) across all trials.

Table 5.1. Kinetic and kinematic variables used to quantify the relationships with physical performance-related variables (taken from Chapter 3).

Kinematic variable	Kinetic variable
Punch delivery time (ms)	Peak lead leg GRF (N/kg)
Peak fist velocity (m/s)	Peak rear leg GRF (N/kg)
Peak shoulder joint angular velocity (deg/s)	Total lead leg net braking impulse (N/s/kg)
Peak elbow joint angular velocity (deg/s)	Total lead leg vertical impulse (N/s/kg)
Timing of peak shoulder joint angular velocity (% of movement)	Total rear leg net propulsive impulse (N/s/kg)
Timing of peak elbow joint angular velocity (% of movement)	Total rear leg vertical impulse (N/s/kg)

Note: ms = milliseconds, m/s = metres per second, deg/s = degrees per second, N/kg = Newtons per kilogram body mass, N/s/kg = Newtons per second per kilogram body mass

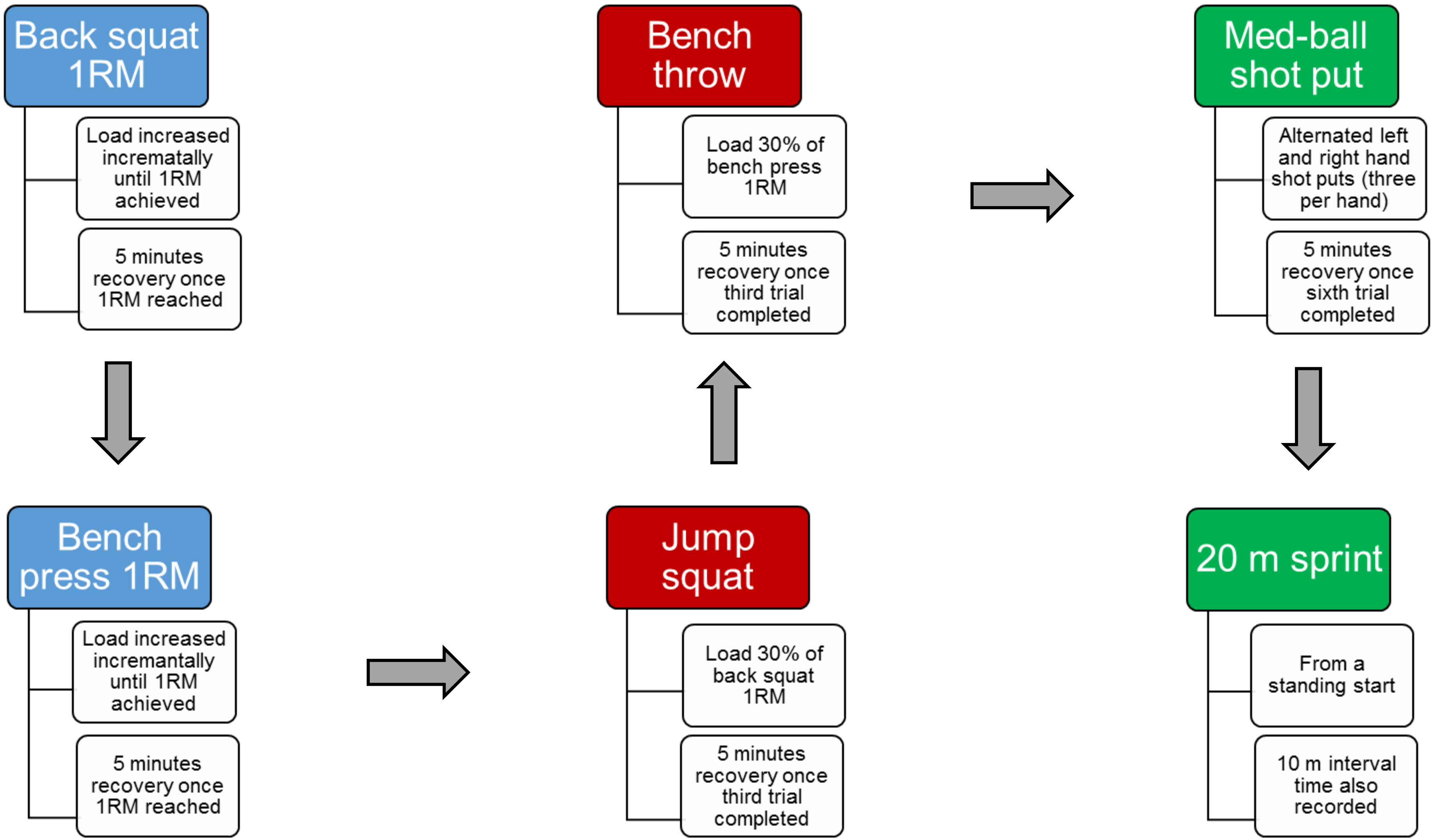

Figure 5.1. Schematic of physical assessment procedure.

Muscular strength was measured via back squat and bench press exercises, respectively, which were selected based on their validity and reliability in quantifying maximal muscular strength (Seo et al., 2012) and inclusion of key movement patterns relating to punching performance (elbow extension and leg drive - Cheraghi et al., 2014; Filimonov et al., 1985). The 1RM testing procedure involved the execution of back squats performed for five to ten repetitions at a load anticipated to be 50% of participant's 1RM (based upon participant suggestion), with load subsequently increased in moderate increments. A 1RM score was achieved once a participant was unable to complete a lift with correct technique (i.e. concentric failure), following the protocol recommended by McGuigan (2016) (see Table 5.2). The same protocol was subsequently followed for the bench press exercise following a 5-minute recovery period from the determination of back squat 1RM. These absolute strength values were also expressed in 'normalised' strength terms ($kg{\cdot}M_b^{-0.67}$) based upon dimensional scaling recommendations whereby load lifted (kg) is divided by body mass and raised to the power of 0.67 $\left((\frac{kg}{kgMb^{0.67}})\right)$ (Helgerud, Rodas, Kemi, & Hoff, 2011). This method prevents underestimation and/or overestimation errors typically associated with standard strength equations (Heil, 1997; Helgerud et al., 2011; Wisløff, Helgerud, & Hoff, 1998).

Following the 1RM tests, lower- and upper-body P_{max} was quantified via jump squats and bench throws, performed with 30% of back squat (jump squat) and bench press (bench throw) 1RM, respectively, based upon the efficacy of this load at inducing P_{max} in both the bench throw (Alemany et al., 2005; Falvo et al., 2006; Thomas et al., 2007) and jump squat (Alemany et al., 2005; Wilson et al., 1993). The jump squat was selected instead of Olympic lifts and their derivatives to assess peak lower-body power due to the negligible experience of the participants with the latter, the technical proficiency/mastery required to execute them efficiently and the high loads (70-90% 1RM) required to express peak power with such lifts (Kawamori et al., 2005; Kilduff et al., 2007; McBride, Haines, & Kirby, 2011). Moreover, loaded jumps have exhibited larger peak power outputs than Olympic lifts in previous research (Cormie et al., 2007b; Kawamori et al. 2006; MacKenzie et al. 2014) and do not require the same technical expertise and loading intensities as Olympic lifts (20% 1RM compared to 70% 1RM - Oranchuk, Robinson, Switaj, & Drinkwater, 2019).

Table 5.2. One-repetition maximum (1RM) testing procedure (McGuigan, 2016).

Load	Repetitions	Rest Periods
50% 1RM	5-10	1 minute
60-75% 1RM	3-5	2 minutes
90% 1RM	2-3	2-4 minutes
First attempt at 1RM	1	2-4 minutes
If successful, weight increased by 4-9 kg (upper-body exercise) or 14-18 kg (lower-body exercise) until 1RM is reached. If unsuccessful, weight decreased by 2-4 kg (upper-body exercise) or 7-9 kg (lower-body exercise) before 1RM is re-attempted.	1	2-4 minutes

On both P_{max} assessments, participants performed three maximal intensity repetitions with each repetition separated by a 3-minute recovery. Jump squats were performed ‘free weight’ with a regular barbell as this variation has demonstrated superior mean power values in comparison to the Smith Machine variation (Sheppard, Doyle, & Taylor, 2008). Meanwhile, bench throws were performed on a Smith Machine to minimise the risks of injury (Kobayashi et al., 2013).

After P_{max} assessments, participants performed lead and rear hand medicine ball shot puts (4 kg) to measure full-body power in a motion possessing similar kinematics to a straight punch. ‘Lead’ and ‘rear’ hands were determined by the preferred boxing stance of each boxer (orthodox (left hand and foot leading) or southpaw (right hand and foot leading) - Hickey, 2006). Previous research has highlighted a strong correlation (r = 0.83) between shot put distance and punching performance among boxers (Obmiński et al., 2011). Lastly, 20 m sprints with timing gates placed at 10 m and 20 m checkpoints quantified short distance linear acceleration and speed (Morin et al., 2015). Sprints over short distances (≤ 20 m) accurately represent maximum linear acceleration and speed capabilities of athletes (Pereira et al., 2018; Young et al., 2008; Young, Benton, & Pryor, 2001), with sprint times over 10 m reported as a good reflection of acceleration capabilities and sprints between 20-40 m as an estimate of maximum speed capabilities (Haff et al., 2016; Young et al., 2008). Moreover, sprint times over such distances have exhibited moderate-to-good test-retest reliability (ICC = 0.71-0.98; 95% LoA = −0.01 to -0.12) and low error (CV = 1.0-3.1%) in previous research across a range of athletes (Darrall-Jones et al., 2016; Foden et al., 2015; Waldron, Worsfold, Twist, & Lamb, 2011), whereas shorter distances have not exhibited such reliability (5 m: ICC = 0.37, CV = 4.5% (Standing & Maulder, 2017)). In line with previous research, each participant started from a staggered stance 0.3 m behind the first timing gate (Foden, et al., 2015; Pereira et al., 2018). Sprint trials were performed across a 45 m stretch of empty space (including a ‘run off’ area) located inside a multi-purpose sports hall. Participants completed three maximal 20 m sprints with four minutes recovery provided between trials.

All boxers were ordered to abstain from consuming any form of caffeinated beverage(s) (i.e. coffee, energy drinks, ‘pre-workout’ sports supplements) prior to the biomechanical and physical performance assessments. This was to ensure performance was not influenced by nutritional aids given the role of caffeine in enhancing measures of muscular strength (Astorino & Roberson, 2010; Duncan, Stanley, Parkhouse, Cook, & Smith, 2013), power (McCormack & Hoffman, 2012) and sprint performance (Trexler, Smith-Ryan, Roelofs, Hirsch, & Mock, 2016). In addition, boxers were also required to abstain from consuming other sports supplements such as creatine, betaine, β-alanine, β-hydroxy β-methylbutyrate (HMB) etc. given the muscular strength, power and hypertrophy increases associated with such supplements (Ismaeel, 2017; Lanhers et al., 2015; 2017; Maté-Muñoz et al., 2018; McIntosh, Love, Haszard, Osborne, & Black, 2018; Nunes et al., 2017). Furthermore, boxers were encouraged to eat a well-balanced diet, with an emphasis on the consumption of lean protein sources (to increase muscle recovery via the triggering of mechanistic/mammalian target of rapamycin (mTOR) and muscle protein synthesis - Kessinger, 2018) and carbohydrates (to increase glucose availability during sessions and encourage muscle glycogen resynthesis - Shamim et al., 2018). Boxers were also encouraged to consume protein and carbohydrate-rich foods (via sports supplements or food) before and after the physical assessments. However, though boxers were encouraged to undertake these nutritional strategies, it should be stated that nutrition was not monitored and/or controlled across the duration of the study.

5.2.4. Statistical analysis

Descriptive statistics (mean ± SD) were generated for all dependent variables (Tables 5.3 to 5.8) and their distributions checked for normality via Shapiro-Wilk tests utilising IBM SPSS (version 23, Chicago, USA). As this condition was met, Pearson product-moment coefficients with 95% confidence intervals were used to assess the relationships between biomechanical variables and performance across various physical tests. In the manner of Hopkins (2002), thresholds were interpreted as: < 0.1 (trivial); 0.1-0.3 (small); 0.3-0.5 (moderate); 0.5-0.7 (large); 0.7-0.9 (very large) and > 0.9 (nearly perfect).

5.3. Results

5.3.1. Muscular strength

Back squat 1RM exhibited very large correlations with peak fist velocities of jab, rear-hand cross (Tables 5.3 and 5.4) and lead hook (Table 5.5) punches (r = 0.70-0.74), while normalised back squat 1RM also showed noteworthy associations with the same punches (jab; r = 0.67, rear-hand cross; r = 1.0 lead hook; r = 0.51). Moreover, moderate correlations were observed for the same variables with rear hook and lead and rear uppercut (Tables 5.6 to 5.8) peak fist velocities (r = 0.31-0.52). Lead uppercut peak lead leg and rear uppercut peak rear leg GRF were both associated with back squat 1RM performance (r = 0.58-0.60), as were lead leg impulses for the rear-hand cross (braking; r = 0.55; vertical; r = 0.56) and rear leg vertical impulse for the rear hook (r = 0.55), respectively.

Numerous variables were positively associated with bench press 1RM, including lead hook and rear uppercut peak fist velocities (r = 0.55-0.60), rear-hand cross peak lead leg GRF (*r* = 0.59), rear uppercut peak rear leg GRF (*r* = 0.61), and lead leg (rear-hand cross; *r* = 0.56-0.58) and rear leg impulses (rear hook; *r* = 0.64-0.68).

5.3.2. Muscular power

Peak lead and rear leg GRF for the rear uppercut (*r* = 0.30-0.38), and lead leg net braking impulse for the jab and lead hook (*r* = 0.30-0.46) exhibited moderate correlations with jump squat P_{max} (Tables 5.3 and 5.5). Jump squat P_{max} was also positively related to timing of peak shoulder angular velocity for the lead hook (*r* = 0.58), Bench throw P_{max} correlated with peak shoulder joint angular velocity of lead hook and lead uppercut punches (*r* = 0.32-0.60), along with peak elbow angular velocity of all lead hand punches (*r* = 0.36-0.52). Bench throw performance was also associated with lead hook timing of peak shoulder joint angular velocity (*r* = 0.63) and rear uppercut peak lead leg GRF (*r* = 0.54). Rear hand medicine ball shot put distance was associated with peak lead leg GRF across all rear hand punches (*r* = 0.58-0.66), while also exhibiting small to moderate associations with peak rear leg GRF for rear hook and rear uppercut punches (*r* = 0.30-0.50).

5.3.3. Speed

Sprint speed over both 10 m and 20 m distances exhibited moderate-to-large associations (Table 5.4) with peak rear leg GRF across rear-hand cross (*r* = 0.65 & 0.58), rear hook (*r* = 0.45 & 0.50), and rear uppercut (*r* = 0.32 & 0.33) punches. Likewise, both were moderately related to timing of peak elbow joint angular velocity of the rear-hand cross (*r* = 0.68 & 0.72) and rear hook (*r* = 0.40 & 0.27), respectively.

Table 5.3. Correlations (± 95% CI) between physical performance-related measures and jab kinetic and kinematic variables

Variable	Back squat 1RM (kg)	Back squat 1RM ($kg \cdot M_b^{-0.67}$)	Bench press 1RM (kg)	Bench press 1RM ($kg \cdot M_b^{-0.67}$)	Jump squat P_{max} (W/kg)	Bench throw P_{max} (W/kg)	Shot put (LH - m)	10 m sprint (s)	20 m sprint (s)
DT	0.42 (-0.13 to 0.99)	0.08 (-0.54 to 0.71)	0.32 (-0.27 to 0.91)	0.06 (-0.55 to 0.69)	**-0.55 (-1.08 to 0.03)**	-0.03 (-0.66 to 0.59)	-0.37 (-0.95 to 0.21)	0.25 (-0.34 to 0.86)	0.30 (-0.29 to 0.90)
FV	**0.74 (0.31 to 1.16)**	**0.67 (0.21 to 1.13)**	0.36 (-0.22 to 0.95)	**0.51 (-0.19 to 1.05)**	0.05 (-0.57 to 0.68)	0.40 (-0.17 to 0.97)	-0.38 (-0.96 to 0.19)	0.33 (-0.26 to 0.92)	0.49 (-0.05 to 1.04)
SJAV	0.39 (0-.18 to 0.97)	0.40 (-0.17 to 0.97)	0.14 (-0.48 to 0.76)	0.08 (-0.53 to 0.71)	-0.30 (-0.90 to 0.29)	0.34 (-0.47 to 0.76)	-0.31 (-0.90 to 0.28)	0.25 (-0.35 to 0.86)	0.29 (-0.30 to 0.89)
EJAV	**0.56 (0.04 to 1.08)**	0.42 (-0.13 to 0.99)	0.32 (-0.27 to 0.91)	0.17 (-0.44 to 0.79)	0.19 (-0.42 to 0.80)	**0.50 (-0.03 to 1.04)**	-0.06 (-0.68 to 0.56)	0.12 (-0.50 to 0.74)	0.17 (-0.44 to 0.79)
SJAV%	-0.16 (-0.78 to 0.45)	-0.14 (-0.76 to 0.47)	-0.09 (-0.71 to 0.53)	-0.06 (-0.69 to 0.55)	-0.16 (-0.78 to 0.45)	-0.48 (-1.03 to 0.07)	-0.08 (-0.71 to 0.54)	0.15 (-0.46 to 0.77)	-0.04 (-0.67 to 0.58)
EJAV%	-0.01 (-0.69 to 0.65)	-0.23 (-0.90 to 0.41)	0.17 (-0.51 to 0.82)	0.04 (-0.63 to 0.72)	-0.62 (-1.18 to -0.10)	-0.27 (-0.93 to 0.37)	-0.10 (-0.76 to 0.54)	0.33 (-0.30 to 0.98)	0.20 (-0.46 to 0.88)
LLGRF	0.22 (-0.38 to 0.83)	-0.17 (-0.79 to 0.44)	0.42 (-0.14 to 0.99)	0.20 (-0.40 to 0.82)	-0.17 (-0.79 to 0.44)	0.001 (-0.62 to 0.63)	0.24 (-0.36 to 0.85)	0.01 (-0.62 to 0.63)	-0.01 (-0.64 to 0.61)
RLGRF	0.26 (-0.33 to 0.87)	-0.01 (-0.64 to 0.61)	0.33 (-0.25 to 0.92)	0.17 (-0.44 to 0.79)	-0.08 (-0.71 to 0.54)	0.31 (-0.28 to 0.90)	0.08 (-0.54 to 0.71)	0.10 (-0.52 to 0.73)	0.01 (-0.62 to 0.63)
LLFyI	0.30 (-0.29 to 0.90)	0.28 (-0.32 to 0.88)	0.11 (-0.51 to 0.73)	0.05 (-0.57 to 0.68)	0.46 (-0.08 to 1.02)	0.46 (-0.09 to 1.02)	0.22 (-0.39 to 0.83)	0.18 (-0.43 to 0.79)	0.33 (-0.26 to 0.92)
LLFzI	0.07 (-0.54 to 0.70)	-0.16 (-0.78 to 0.46)	0.12 (-0.49 to 0.75)	-0.01 (-0.64 to 0.61)	-0.35 (-0.93 to 0.29)	-0.25 (-0.96 to 0.34)	-0.27 (-0.88 to 0.32)	0.23 (-0.37 to 0.84)	0.07 (-0.55 to 0.70)
RLFyI	0.35 (-0.23 to 0.94)	0.004 (-0.62 to 0.63)	0.40 (-0.17 to 0.97)	0.18 (-0.43 to 0.80)	-0.36 (-0.95 to 0.21)	0.23 (-0.38 to 0.84)	-0.07 (-0.70 to 0.55)	-0.004 (-0.63 to 0.62)	0.04 (-0.58 to 0.67)
RLFzI	0.38 (-0.20 to 0.96)	-0.18 (-0.43 to 0.80)	0.39 (-0.18 to 0.97)	0.26 (-0.33 to 0.87)	-0.47 (-1.02 to 0.07)	0.09 (-0.53 to 0.72)	-0.30 (-0.90 to 0.29)	0.08 (-0.53 to 0.71)	0.08 (-0.54 to 0.70)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse, LH = lead hand, RH = rear hand, kg = kilograms, M_b = body mass, N/kg = Newtons per kilogram body mass, W/kg = Watts per kilogram body mass, m = metres, s = seconds, bold text indicates large, very large and nearly perfect (*r* = ≥ 0.50) correlations.

Table 5.4. Correlations (± 95% CI) between physical performance-related measures and rear-hand cross kinetic and kinematic variables.

Variable	Back squat 1RM (kg)	Back squat 1RM ($\text{kg}\cdot M_b^{-0.67}$)	Bench press 1RM (kg)	Bench press 1RM ($\text{kg}\cdot M_b^{-0.67}$)	Jump squat P_{max} (W/kg)	Bench throw P_{max} (W/kg)	Shot put (RH - m)	10 m sprint (s)	20 m sprint (s)
DT	0.42 (-0.14 to 0.99)	0.36 (-0.21 to 0.95)	0.36 (-0.21 to 0.95)	0.32 (-0.27 to 0.91)	**0.60** (0.10 to 1.10)	0.04 (-0.58 to 0.67)	-0.26 (-0.87 to 0.33)	0.08 (-0.54 to 0.71)	0.24 (-0.36 to 0.85)
FV	**0.70 (0.26 to 1.15)**	**1.00 (1.00 to 1.00)**	**0.51 (-0.29 to 1.00)**	**0.61 (0.11 to 1.11)**	0.12 (-0.49 to 0.75)	**0.50 (-0.04 to 1.04)**	0.02 (-0.60 to 0.65)	0.44 (-0.11 to 1.01)	**0.50 (-0.03 to 1.04)**
SJAV	-0.39 (-0.97 to 0.18)	-0.29 (-0.89 to 0.31)	-0.31 (-0.90 to 0.28)	-0.22 (-0.83 to 0.38)	-0.09 (-0.71 to 0.53)	-0.05 (-0.68 to 0.58)	-0.34 (-0.93 to 0.25)	0.10 (-0.52 to 0.72)	0.17 (-0.44 to 0.79)
EJAV	-0.30 (-0.90 to 0.29)	-0.47 (-1.02 to 0.07)	-0.11 (-0.73 to 0.51)	-0.17 (-0.79 to 0.44)	-0.19 (-0.81 to 0.41)	0.05 (-0.57 to 0.68)	0.02 (-0.65 to 0.60)	0.03 (-0.59 to 0.65)	0.03 (-0.59 to 0.66)
SJAV%	0.23 (-0.41 to 0.89)	0.17 (-0.49 to 0.84)	0.27 (-0.37 to 0.93)	0.24 (-0.40 to 0.91)	-0.13 (-0.82 to 0.54)	-0.26 (-0.92 to 0.38)	0.09 (-0.58 to 0.77)	0.45 (-0.14 to 1.07)	0.39 (-0.21 to 1.04)
EJAV%	0.22 (-0.42 to 0.88)	-0.10 (-0.78 to 0.56)	-0.20 (-0.86 to 0.45)	**-0.53 (-1.12 to 0.02)**	-0.34 (-1.00 to 0.28)	-0.38 (-1.02 to 0.23)	-0.28 (-0.94 to 0.36)	**0.68 (0.20 to 1.20)**	**0.72 (0.28 to 1.22)**
LLGRF	**0.44 (-0.12 to 1.00)**	-0.06 (-0.69 to 0.56)	**0.59 (0.09 to 1.10)**	0.30 (-0.29 to 0.90)	0.09 (-0.53 to 0.72)	0.29 (-0.31 to 0.89)	**0.66 (0.19 to 1.13)**	0.01 (-0.62 to 0.63)	-0.02 (-0.65 to 0.60)
RLGRF	0.35 (-0.23 to 0.94)	0.05 (-0.57 to 0.68)	0.29 (-0.30 to 0.89)	0.09 (-0.53 to 0.71)	-0.05 (-0.68 to 0.57)	0.13 (-0.48 to 0.75)	0.19 (-0.42 to 0.80)	**0.65 (0.17 to 1.13)**	**0.58** (0.07 to 1.09)
LLFyI	**0.55 (0.02 to 1.07)**	-0.37 (-0.95 to 0.21)	**0.58 (0.07 to 1.09)**	-0.47 (-1.02 to 0.07)	0.28 (-0.31 to 0.88)	0.24 (-0.85 to 0.37)	0.04 (-0.67 to 0.58)	0.06 (-0.56 to 0.69)	0.11 (-0.73 to 0.51)
LLFzI	**0.56 (0.04 to 1.08)**	0.42 (-0.15 to 0.99)	**0.56 (0.04 to 1.08)**	0.47 (-0.07 to 1.03)	-0.30 (-0.90 to 0.29)	0.25 (-0.34 to 0.86)	-0.03 (-0.65 to 0.59)	-0.10 (-0.64 to 0.61)	0.16 (-0.46 to 0.78)
RLFyI	0.45 (-0.11 to 1.01)	0.31 (-0.28 to 0.91)	0.49 (-0.04 to 1.04)	0.42 (-0.14 to 0.99)	-0.35 (-0.94 to 0.23)	0.17 (-0.44 to 0.79)	-0.07 (-0.70 to 0.54)	0.02 (-0.60 to 0.65)	0.18 (-0.43 to 0.80)
RLFzI	0.41 (-0.16 to 0.98)	-0.42 (-0.13 to 0.99)	0.47 (-0.08 to 1.02)	**0.50 (-0.04 to 1.04)**	-0.31 (-0.91 to 0.27)	0.22 (-0.38 to 0.83)	-0.18 (-0.80 to 0.43)	-0.07 (-0.69 to 0.55)	0.08 (-0.54 to 0.71)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse, LH = lead hand, RH = rear hand, kg = kilograms, M_b = body mass, N/kg = Newtons per kilogram body mass, W/kg = Watts per kilogram body mass, m = metres, s = seconds, bold text indicates large, very large and nearly perfect (r = ≥ 0.50) correlations.

Table 5.5. Correlations (± 95% CI) between physical performance-related measures and lead hook kinetic and kinematic variables.

Variable	Back squat 1RM (kg)	Back squat 1RM ($kg \cdot M_b^{-0.67}$)	Bench press 1RM (kg)	Bench press 1RM ($kg \cdot M_b^{-0.67}$)	Jump squat P_{max} (W/kg)	Bench throw P_{max} (W/kg)	Shot put (LH - m)	10 m sprint (s)	20 m sprint (s)
DT	-0.10 (-0.72 to 0.52)	-0.10 (-0.73 to 0.51)	0.02 (-0.60 to 0.65)	0.04 (-0.58 to 0.67)	**-0.55 (-1.08 to 0.03)**	-0.14 (-0.77 to 0.47)	-0.29 (-0.89 to 0.30)	-0.26 (-0.87 to 0.34)	-0.27 (-0.87 to 0.33)
FV	**0.73 (0.30 to 1.16)**	**0.51 (-0.02 to 1.05)**	**0.60 (0.10 to 1.10)**	0.42 (-0.13 to 0.99)	0.31 (-0.28 to 0.90)	0.36 (-0.21 to 0.95)	-0.01 (-0.64 to 0.61)	0.36 (-0.21 to 0.95)	0.44 (-0.11 to 1.01)
SJAV	0.35 (-0.23 to 0.94)	0.31 (-0.28 to 0.90)	0.29 (-0.31 to 0.89)	0.24 (-0.36 to 0.85)	0.43 (-0.13 to 1.00)	**0.60** (0.09 to 1.10)	-0.16 (-0.78 to 0.46)	0.14 (-0.47 to 0.77)	0.29 (-0.31 to 0.89)
EJAV	**0.53** (0.006 to 1.06)	0.42 (-0.14 to 0.99)	0.18 (-0.43 to 0.80)	0.02 (-0.60 to 0.65)	0.39 (-0.18 to 0.97)	0.36 (-0.22 to 0.95)	0.03 (-0.59 to 0.66)	0.36 (-0.22 to 0.94)	0.34 (-0.25 to 0.93)
SJAV%	0.20 (-0.40 to 0.82)	0.13 (-0.49 to 0.75)	0.44 (-0.12 to 1.00)	0.45 (-0.10 to 1.01)	**0.58 (0.07 to 1.09)**	**0.63 (0.14 to 1.12)**	0.40 (-0.17 to 0.97)	**-0.54 (-1.07 to 0.01)**	-0.44 (-1.01 to 0.11)
EJAV%	-0.10 (-0.72 to 0.52)	-0.19 (-0.81 to 0.42)	-0.30 (-0.90 to 0.29)	-0.42 (-0.99 to 0.15)	-0.49 (-1.04 to 0.04)	-0.44 (-1.00 to 0.11)	-0.14 (-0.76 to 0.47)	0.11 (-0.50 to 0.74)	-0.01 (-0.64 to 0.61)
LLGRF	0.23 (-0.38 to 0.84)	-0.19 (-0.81 to 0.42)	0.19 (-0.42 to 0.81)	-0.10 (-0.73 to 0.52)	-0.07 (-0.70 to 0.55)	0.04 (-0.58 to 0.67)	0.04 (-0.58 to 0.66)	0.25 (-0.35 to 0.86)	0.29 (-0.30 to 0.89)
RLGRF	-0.07 (-0.70 to 0.55)	-0.22 (-0.83 to 0.39)	0.30 (-0.29 to 0.90)	0.30 (-0.29 to 0.90)	0.03 (-0.59 to 0.66)	0.15 (-0.46 to 0.77)	0.34 (-0.24 to 0.93)	-0.25 (-0.85 to 0.35)	-0.40 (-0.97 to 0.17)
LLFyI	**0.70 (0.26 to 1.15)**	-0.16 (-0.78 to 0.45)	-0.10 (-0.64 to 0.61)	-0.18 (-0.80 to 0.43)	0.30 (-0.29 to 0.90)	**-0.50 (-0.67 to 0.57)**	0.38 (-0.10 to 0.96)	0.41 (-0.16 to 0.98)	0.30 (-0.29 to 0.90)
LLFzI	**0.70 (0.26 to 1.15)**	-0.18 (-0.79 to 0.43)	0.12 (-0.50 to 0.74)	0.09 (-0.52 to 0.72)	-0.34 (-0.93 to 0.24)	-0.01 (-0.63 to 0.61)	-0.05 (-0.67 to 0.57)	-0.30 (-0.90 to 0.29)	-0.32 (-0.92 to 0.26)
RLFyI	-0.22 (-0.84 to 0.38)	-0.15 (-0.78 to 0.46)	0.04 (-0.58 to 0.67)	0.15 (-0.46 to 0.77)	-0.26 (-0.87 to 0.33)	-0.06 (-0.69 to 0.55)	-0.19 (-0.81 to 0.42)	**0.52 (-0.005 to 1.06)**	-0.49 (-1.04 to 0.05)
RLFzI	-0.20 (-0.82 to 0.41)	-0.07 (-0.70 to 0.55)	0.12 (-0.50 to 0.74)	0.29 (-0.30 to 0.89)	-0.32 (-0.91 to 0.27)	-0.05 (-0.68 to 0.57)	-0.12 (-0.74 to 0.49)	-0.46 (-1.02 to 0.09)	**0.50 (-0.04 to 1.04)**

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse, LH = lead hand, RH = rear hand, kg = kilograms, M_b = body mass, N/kg = Newtons per kilogram body mass, W/kg = Watts per kilogram body mass, m = metres, s = seconds, bold text indicates large, very large and nearly perfect (*r* = ≥ 0.50) correlations.

Table 5.6. Correlations (± 95% CI) between physical performance-related measures and rear hook kinetic and kinematic variables.

Variable	Back squat 1RM (kg)	Back squat 1RM ($kg \cdot M_b^{-0.67}$)	Bench press 1RM (kg)	Bench press 1RM ($kg \cdot M_b^{-0.67}$)	Jump squat P_{max} (W/kg)	Bench throw P_{max} (W/kg)	Shot put (RH - m)	10 m sprint (s)	20 m sprint (s)
DT	0.30 (-0.29 to 0.90)	-0.18 (-0.79 to 0.43)	0.39 (-0.18 to 0.97)	0.09 (-0.53 to 0.72)	-0.24 (-0.85 to 0.36)	-0.01 (-0.64 to 0.61)	0.25 (-0.35 to 0.86)	-0.21 (-0.83 to 0.39)	-0.09 (-0.72 to 0.53)
FV	0.41 (-0.15 to 0.98)	0.31 (-0.28 to 0.91)	0.30 (-0.29 to 0.90)	0.21 (-0.40 to 0.82)	0.13 (-0.48 to 0.76)	0.34 (-0.25 to 0.93)	-0.02 (-0.65 to 0.60)	0.17 (-0.45 to 0.79)	0.34 (-0.24 to 0.93)
SJAV	-0.38 (-0.96 to 0.19)	-0.36 (-0.94 to 0.22)	-0.41 (-0.89 to 0.15)	-0.41 (-0.98 to 0.16)	-0.03 (-0.66 to 0.59)	0.09 (-0.53 to 0.71)	-0.23 (-0.84 to 0.37)	0.12 (-0.50 to 0.74)	0.22 (-0.39 to 0.83)
EJAV	-0.10 (-0.73 to 0.52)	-0.11 (-0.73 to 0.51)	-0.12 (-0.75 to 0.49)	-0.14 (-0.76 to 0.47)	-0.09 (-0.71 to 0.53)	-0.01 (-0.64 to 0.61)	-0.34 (-0.93 to 0.25)	-0.04 (-0.67 to 0.58)	-0.07 (-0.70 to 0.55)
SJAV%	0.15 (-0.46 to 0.77)	0.05 (-0.57 to 0.68)	0.01 (-0.61 to 0.64)	-0.07 (-0.70 to 0.54)	0.02 (-0.60 to 0.64)	0.13 (-0.48 to 0.76)	-0.14 (-0.76 to 0.48)	-0.11 (-0.73 to 0.51)	-0.29 (-0.89 to 0.30)
EJAV%	0.05 (-0.63 to 0.74)	-0.19 (-0.86 to 0.47)	-0.23 (-0.86 to 0.39)	-0.48 (-1.03 to 0.09)	**-0.51 (-0.99 to 0.05)**	-0.34 (-0.96 to 0.27)	-0.27 (-0.93 to 0.38)	0.40 (-0.20 to 1.03)	0.27 (-0.38 to 0.93)
LLGRF	0.20 (-0.41 to 0.82)	-0.30 (-0.90 to 0.30)	0.36 (-0.22 to 0.94)	0.07 (-0.54 to 0.70)	0.22 (-0.38 to 0.84)	0.26 (-0.34 to 0.86)	**0.58 (0.06 to 1.09)**	0.06 (-0.55 to 0.69)	-0.09 (-0.72 to 0.52)
RLGRF	0.39 (-0.18 to 0.97)	-0.06 (-0.56 to 0.69)	0.34 (-0.24 to 0.93)	0.11 (-0.51 to 0.73)	0.18 (-0.43 to 0.80)	0.15 (-0.46 to 0.77)	0.30 (-0.29 to 0.90)	0.45 (-0.10 to 1.01)	**0.50 (-0.04 to 1.04)**
LLFyI	-0.34 (-0.93 to 0.24)	0.04 (-0.58 to 0.66)	-0.44 (-1.00 to 0.12)	-0.21 (-0.82 to 0.40)	0.01 (-0.62 to 0.63)	-0.12 (-0.74 to 0.50)	-0.37 (-0.96 to 0.20)	0.22 (-0.38 to 0.83)	0.16 (-0.45 to 0.78)
LLFzI	0.16 (-0.45 to 0.78)	-0.24 (-0.85 to 0.37)	0.28 (-0.32 to 0.88)	0.04 (-0.58 to 0.67)	-0.02 (-0.65 to 0.60)	0.01 (-0.62 to 0.63)	0.33 (-0.25 to 0.92)	-0.23 (-0.84 to 0.38)	-0.17 (-0.79 to 0.44)
RLFyI	**0.52 (-0.005 to 1.06)**	-0.01 (-0.64 to 0.61)	**0.64 (0.15 to 1.12)**	0.30 (-0.28 to 0.90)	-0.05 (-0.68 to 0.57)	0.19 (-0.41 to 0.81)	**0.51 (-0.02 to 1.05)**	-0.08 (-0.71 to 0.54)	-0.01 (-0.63 to 0.61)
RLFzI	**0.55 (0.02 to 1.07)**	0.08 (-0.54 to 0.71)	**0.68 (0.23 to 1.14)**	0.41 (-0.15 to 0.98)	-0.05 (-0.67 to 0.57)	0.22 (0.38 to 0.84)	0.45 (-0.10 to 1.01)	-0.17 (-0.79 to 0.44)	-0.06 (-0.69 to 0.56)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse, LH = lead hand, RH = rear hand, kg = kilograms, M_b = body mass, N/kg = Newtons per kilogram body mass, W/kg = Watts per kilogram body mass, m = metres, s = seconds, bold text indicates large, very large and nearly perfect (r = ≥ 0.50) correlations.

Table 5.7. Correlations (± 95% CI) between physical performance-related measures and lead uppercut kinetic and kinematic variables.

Variable	Back squat 1RM (kg)	Back squat 1RM (kg·$M_b^{-0.67}$)	Bench press 1RM (kg)	Bench press 1RM (kg·$M_b^{-0.67}$)	Jump squat P_{max} (W/kg)	Bench throw P_{max} (W/kg)	Shot put (LH - m)	10 m sprint (s)	20 m sprint (s)
DT	-0.32 (-0.92 to 0.26)	-0.43 (-1.00 to 0.12)	-0.14 (-0.76 to 0.47)	-0.17 (-0.79 to 0.44)	**-0.69 (-1.14 to -0.24)**	-0.33 (-0.92 to 0.26)	-0.13 (-0.75 to 0.48)	-0.13 (-0.75 to 0.48)	-0.14 (-0.76 to 0.47)
FV	0.42 (-0.14 to 0.99)	0.30 (-0.29 to 0.90)	0.18 (-0.43 to 0.80)	0.03 (-0.59 to 0.66)	0.28 (-0.31 to 0.88)	0.11 (-0.51 to 0.73)	-0.28 (-0.81 to 0.41)	0.36 (-0.21 to 0.95)	0.43 (-0.13 to 0.99)
SJAV	0.41 (-0.15 to 0.99)	0.46 (-0.08 to 1.02)	0.27 (-0.33 to 0.87)	0.26 (-0.34 to 0.87)	0.23 (-0.38 to 0.84)	0.32 (-0.27 to 0.91)	-0.34 (-0.93 to 0.24)	0.09 (-0.53 to 0.71)	0.20 (-0.41 to 0.82)
EJAV	0.41 (-0.16 to 0.98)	0.44 (-0.12 to 1.00)	0.28 (-0.32 to 0.88)	0.28 (-0.32 to 0.88)	**0.51 (-0.02 to 1.05)**	**0.52 (-0.01 to 1.05)**	0.29 (-0.31 to 0.89)	-0.08 (-0.71 to 0.54)	0.01 (-0.61 to 0.64)
SJAV%	-0.29 (-0.89 to 0.31)	-0.42 (-0.99 to 0.15)	-0.40 (-0.97 to 0.17)	**-0.52 (-1.06 to 0.005)**	**0.70 (0.26 to 1.15)**	**-0.59 (-1.10 to -0.09)**	-0.44 (-1.01 to 0.11)	0.21 (-0.39 to 0.83)	0.22 (-0.38 to 0.84)
EJAV%	-0.02 (-0.65 to 0.60)	-0.27 (-0.88 to 0.32)	-0.10 (-0.73 to 0.51)	-0.30 (-0.90 to 0.30)	-0.38 (-0.96 to 0.19)	-0.30 (-0.90 to 0.29)	-0.11 (-0.73 to 0.51)	-0.15 (-0.77 to 0.46)	-0.16 (-0.78 to 0.45)
LLGRF	**0.58 (0.06 to 1.09)**	-0.03 (-0.66 to 0.59)	0.36 (-0.21 to 0.95)	-0.08 (-0.71 to 0.54)	0.07 (-0.55 to 0.70)	0.34 (-0.25 to 0.93)	0.20 (-0.41 to 0.81)	0.36 (-0.22 to 0.95)	0.37 (-0.20 to 0.95)
RLGRF	0.01 (-0.61 to 0.64)	-0.05 (-0.68 to 0.57)	0.36 (-0.22 to 0.94)	0.40 (-0.17 to 0.97)	0.10 (-0.52 to 0.72)	0.04 (-0.58 to 0.67)	0.20 (-0.41 to 0.81)	-0.14 (-0.76 to 0.47)	-0.23 (-0.84 to 0.37)
LLFyI	0.06 (-0.55 to 0.69)	0.23 (-0.38 to 0.84)	-0.05 (-0.67 to 0.57)	0.02 (-0.60 to 0.64)	0.23 (-0.37 to 0.84)	-0.15 (-0.77 to 0.47)	-0.07 (-0.70 to 0.55)	**0.50 (-0.04 to 1.04)**	**0.50 (-0.03 to 1.04)**
LLFzI	-0.14 (-0.77 to 0.47)	-0.45 (-1.01 to 0.10)	0.08 (-0.54 to 0.71)	-0.06 (-0.68 to 0.56)	-0.35 (-0.94 to 0.23)	0.07 (-0.55 to 0.70)	0.20 (-0.40 to 0.82)	-0.25 (-0.86 to 0.35)	-0.24 (-0.85 to 0.37)
RLFyI	-0.38 (-0.96 to 0.19)	-0.44 (-1.01 to 0.11)	0.01 (-0.61 to 0.64)	0.08 (-0.54 to 0.70)	-0.19 (-0.81 to 0.42)	0.09 (-0.53 to 0.72)	0.16 (-0.45 to 0.78)	-0.48 (-1.03 to 0.06)	-0.49 (-1.04 to 0.04)
RLFzI	**-0.50 (-1.04 to 0.03)**	-0.44 (-1.00 to 0.11)	-0.01 (-0.63 to 0.61)	0.15 (-0.46 to 0.77)	-0.30 (-0.90 to 0.29)	-0.07 (-0.69 to 0.55)	0.17 (0.44 to 0.79)	-0.47 (-1.02 to 0.08)	**-0.51 (-1.05 to 0.01)**

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse, LH = lead hand, RH = rear hand, kg = kilograms, M_b = body mass, N/kg = Newtons per kilogram body mass, W/kg = Watts per kilogram body mass, m = metres, s = seconds, bold text indicates large, very large and nearly perfect (r = ≥ 0.50) correlations.

Table 5.8. Correlations (± 95% CI) between physical performance-related measures and rear uppercut kinetic and kinematic variables.

Variable	Back squat 1RM (kg)	Back squat 1RM ($kg \cdot M_b^{-0.67}$)	Bench press 1RM (kg)	Bench press 1RM ($kg \cdot M_b^{-0.67}$)	Jump squat P_{max} (W/kg)	Bench throw P_{max} (W/kg)	Shot put (RH - m)	10 m sprint (s)	20 m sprint (s)
DT	-0.13 (-0.75 to 0.49)	-0.08 (-0.71 to 0.54)	0.01 (-0.62 to 0.63)	0.07 (-0.55 to 0.70)	**-0.60 (-1.10 to -0.11)**	-0.29 (-0.89 to 0.31)	-0.36 (-0.94 to 0.22)	0.03 (-0.59 to 0.66)	-0.07 (-0.70 to 0.55)
FV	0.47 (-0.08 to 1.02)	**0.52 (0.006 to 1.06)**	**0.55 (0.26 to 1.07)**	**0.61 (0.11 to 1.10)**	0.08 (-0.53 to 0.71)	0.36 (-0.21 to 0.95)	0.24 (-0.36 to 0.85)	-0.08 (-0.71 to 0.53)	0.05 (-0.56 to 0.68)
SJAV	-0.33 (-0.93 to 0.25)	-0.05 (-0.68 to 0.57)	-0.47 (-1.02 to 0.07)	-0.33 (-0.92 to 0.25)	-0.13 (-0.75 to 0.49)	-0.19 (-0.81 to 0.41)	**-0.50 (-1.05 to 0.03)**	-0.07 (-0.69 to 0.55)	0.08 (-0.54 to 0.70)
EJAV	-0.33 (-0.92 to 0.25)	-0.31 (-0.91 to 0.28)	-0.25 (-0.86 to 0.35)	-0.22 (-0.83 to 0.39)	-0.15 (-0.78 to 0.46)	-0.05 (-0.68 to 0.57)	-0.38 (-0.96 to 0.19)	-0.09 (-0.72 to 0.52)	-0.19 (-0.80 to 0.42)
SJAV%	0.14 (-0.48 to 0.76)	0.21 (-0.40 to 0.82)	0.07 (-0.55 to 0.70)	0.10 (-0.52 to 0.72)	-0.29 (-0.89 to 0.30)	-0.24 (-0.85 to 0.36)	-0.25 (-0.86 to 0.35)	0.26 (-0.33 to 0.87)	0.24 (-0.36 to 0.85)
EJAV%	-0.40 (-0.98 to 0.16)	-0.38 (-0.96 to 0.19)	-0.46 (-1.01 to 0.09)	-0.46 (-1.02 to 0.09)	-0.19 (-0.81 to 0.42)	-0.29 (-0.89 to 0.31)	-0.36 (-0.95 to 0.21)	-0.21 (-0.82 to 0.40)	-0.24 (-0.85 to 0.36)
LLGRF	0.42 (-0.15 to 0.99)	-0.05 (-0.67 to 0.57)	0.43 (-0.12 to 1.00)	0.14 (-0.48 to 0.76)	0.38 (-0.19 to 0.96)	**0.54 (0.01 to 1.07)**	**0.64 (0.16 to 1.12)**	0.02 (-0.60 to 0.65)	-0.03 (-0.66 to 0.59)
RLGRF	**0.60 (0.11 to 1.10)**	0.15 (-0.46 to 0.77)	**0.61 (0.12 to 1.11)**	0.32 (-0.27 to 0.91)	0.30 (-0.29 to 0.90)	0.37 (-0.20 to 0.95)	**0.50 (-0.04 to 1.04)**	0.32 (-0.27 to 0.91)	0.33 (-0.26 to 0.92)
LLFyI	-0.21 (-0.83 to 0.39)	-0.19 (-0.80 to 0.42)	-0.22 (-0.83 to 0.39)	-0.20 (-0.82 to 0.41)	-0.07 (-0.69 to 0.55)	-0.33 (-0.93 to 0.25)	-0.26 (-0.87 to 0.34)	0.26 (-0.34 to 0.87)	0.04 (-0.58 to 0.67)
LLFzI	-0.34 (-0.93 to 0.24)	-0.30 (-0.90 to 0.29)	-0.18 (-0.80 to 0.43)	-0.11 (-0.74 to 0.51)	-0.35 (-0.93 to 0.29)	-0.23 (-0.84 to 0.37)	-0.30 (-0.90 to 0.29)	-0.17 (-0.79 to 0.44)	-0.18 (-0.80 to 0.42)
RLFyI	0.27 (-0.33 to 0.87)	-0.13 (-0.48 to 0.75)	0.35 (-0.23 to 0.94)	0.29 (-0.30 to 0.89)	0.13 (-0.48 to 0.75)	0.43 (-0.13 to 0.99)	0.40 (-0.17 to 0.98)	-0.27 (-0.87 to 0.33)	-0.05 (-0.68 to 0.57)
RLFzI	-0.05 (-0.68 to 0.57)	-0.07 (-0.70 to 0.55)	0.28 (-0.31 to 0.88)	0.36 (-0.22 to 0.94)	-0.03 (-0.66 to 0.59)	0.11 (-0.50 to 0.74)	-0.01 (-0.64 to 0.61)	-0.30 (-0.90 to 0.29)	-0.35 (-0.94 to 0.23)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, SJAV% = timing of peak shoulder joint resultant angular velocity, EJAV% = timing of peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse, LH = lead hand, RH = rear hand, kg = kilograms, M_b = body mass, N/kg = Newtons per kilogram body mass, W/kg = Watts per kilogram body mass, m = metres, s = seconds, bold text indicates large, very large and nearly perfect (r = ≥ 0.50) correlations.

5.4. Discussion

This investigation among experienced amateur boxers has established that dynamic measures of strength, power and speed are associated with a multitude of biomechanical features comprising different punch techniques. The kinetics and kinematics of straight punches were largely influenced by lower-body muscular strength, with moderate relationships observed for both jab and rear-hand cross punches. Meanwhile, moderate correlations were also observed between lead hook kinetics and kinematics and 20m sprint speed, in addition to rear hook variables and upper-body strength, respectively. For uppercuts, the lead punch was most strongly associated with lower-body power, and the rear uppercut with full-body power. Moreover, upper- and lower-body strength influenced peak fist velocity across most punch types, while upper-body power was associated with peak angular shoulder and elbow joint velocities across all lead hand punches. Furthermore, lower-body power exhibited relationships with rear uppercut peak lead and rear leg GRF, rear hand medicine ball shot put distance related to peak lead leg GRF of all rear hand punch types, while peak rear leg GRF of all rear hand punches was associated with 10 m and 20 m sprint speeds, respectively. These novel findings reflect that muscular strength, power and speed qualities (particularly of the lower-limbs) are determinants of the kinetic and kinematic characteristics of maximal punching across all punch types fundamental to boxing, and suggest that attempts by coaches and boxers to augment these qualities may enhance boxing performance.

Whilst previous research has not investigated the associations between dynamic lower-body strength and maximal punch fist velocities, the importance of isometric lower-body force has been determined in facilitating fist acceleration among karatekas (Loturco et al., 2014) and impact force in amateur boxers (Loturco et al., 2016). The current very large (jab, rear-hand cross and lead hook) and moderate (rear hook, lead and rear uppercuts) relationships between back squat 1RM and peak fist velocity (in addition to the moderate-to-perfect associations with normalised back squat 1RM) also implicate lower-body strength in the generation of high fist velocities, and across all fundamental punch types. This may result from the combination of lower-limb kinematics (joint extensions, rotations and angular velocities) and kinetics (joint moments, GRF and impulse) that assist in the transmission of forces distally to the punching fist via the sequential transfer of momentum (Cabral et al., 2010; Cheraghi et al., 2014) during certain punch types. For example, in the case of the rear-hand cross, peak rear leg GRF (57%) occurs prior to peak angular extension velocities of the rear ankle (65%), knee (70%) and hip (72%), whilst peak shoulder (91%) and elbow (99%) joint angular velocities occur towards the end of the punching motion (Chapter 3). This may also help explain the moderate association between jab and lead hook peak elbow angular velocities and back squat 1RM performance, whereby the elbow joint facilitates the transmission of kinetic energy/momentum. Indeed, in the lead hook for example, peak ankle joint angular extension velocity (66%) and extensor moment (76%) assist in generating kinetic energy that is subsequently transferred distally via knee (77%) and hip (79%) joint extension velocities before reaching the elbow (81%) (Chapter 3).

Unlike the data relating to lower-body strength, the observed relationships between bench press 1RM and peak fist velocities (of the rear-hand cross, lead hook, and rear uppercut) are comparable to those of Kim et al. (2018) who reported a moderate relationship (r = 0.51) between bench press strength and straight punch impact power. This finding also corroborates to some extent the link previously established by Loturco et al. (2014), albeit their study reported correlations (r = 0.70-

0.76) between dynamic upper-body strength and fist acceleration (of rear-hand straight punches) among elite karate practitioners. Nonetheless, these findings may be due to the influence of muscular strength to force-time characteristics (e.g. rate of force development, neuromuscular power) which can be effectively translated to dynamic athletic activities (Suchomel et al., 2016). Indeed, the strength of upper-extremity joints and surrounding musculature are important to the generation of high fist velocities (López-Laval et al., 2019; Tasiopoulos et al., 2015; 2018) as the shoulder and elbow joints assist in the transference of kinetic energy and momentum generated by lower-limb kinematics (ankle, knee and hip joint extension angles and angular extension velocities) and kinetics (ankle, knee and hip joint extensor moments) to the punching fist during maximal punches (Chapter 3). The implications for enhancing fist kinematics via specific upper-body conditioning exercise are a greater likelihood of landing clean punches due to a reduction in reaction time afforded to an opponent to defend/evade punches, and an increase in the damage potential of punches resulting from an increase in impact force (based upon the impulse-momentum relationship whereby an increase in fist velocity will yield an increase in momentum (mass x velocity)) and subsequently more force being imparted (impulse = force x time) (Turner et al., 2011).

The moderate-to-large positive associations between back squat 1RM and peak lead leg GRF for both uppercut punches, in addition to lead leg (net braking and vertical - rear-hand cross) and rear leg (net propulsive and vertical - jab and rear hook) impulses suggest that boxers with stronger lower-limb musculature are able to produce larger lower-limb force (GRF and impulse, lower-limb joint extension angles, angular extension velocities and extensor moments), even when normalised to kg body mass. Indeed, previous research has reported that high levels of muscular strength augment force-time characteristics across the whole force-velocity curve, and that the greater the lower-limb strength possessed by an athlete, the greater the lower-limb kinetic energy generated (Spiteri, Cochran, Hart, Haff, & Nimphius, 2013; Stone et al., 2003; Suchomel et al., 2016). Moreover, lower-limb force is also reported to be critical to maximising the performance of dynamic full-body actions wherein the kinematics are similar to punching, with the rear leg generating force via ankle, knee and hip joint extensions, extension velocities, and extensor moments, and the lead leg providing a stable, rigid base that facilitate the transfer of kinetic energy through the hips, trunk and upper-limbs (kinetic chain) (via lower-limb joint kinematics and moments), to the upper-limbs (Chapter 3; MacWilliams et al. 1998; Matsuo et al., 2001; McNally et al., 2015; Terzis, Kyriazis, Karampatsos, & Giorgiadis, 2012; Whiting, Gregor, & Halushka, 1991). Indeed, it appears that lower-limb joint extension angles in conjunction with angular extension velocities and extensor moments facilitate the generation of GRF and impulse via the sequential transfer of energy via the lower-limb kinetic chain that is subsequently transmitted through the hips, trunk and upper-limbs before being imparted on the target via the fist (Cabral et al, 2010; Chapter 3; Cheraghi et al., 2014). This has been evidenced for the rear uppercut in previous research whereby peak rear leg joint angular extension velocities (ankle - 59%, knee - 66%, hip - 69%) generate kinetic energy/momentum that are transferred to upper limbs (elbow – 75%, shoulder – 96%), with the assistance of lead leg extension velocities (ankle - 72%, knee - 78%, hip - 79%) (Chapter 3).

Consequently, as previous research has highlighted the importance of lower-body strength to the end-point impact kinetics of maximal punching (Del Vecchio et al., 2017; 2019; Loturco et al., 2014; 2016), the development of a boxer’s lower-limb dynamic strength (via RT interventions) will likely strengthen other kinematic and kinetic qualities associated with maximal punching, such as joint velocities, punch delivery time and peak GRF. Moderate associations observed between jump squat P_{max} and peak lead and rear leg GRF for the rear uppercut highlight the relevance of lower-limb power to this punch. Indeed, as only trivial-to-small correlations were observed between jump squat performance and peak GRF across other punch types, it seems plausible that force orientation is a causative feature in this relationship (Morin et al., 2011; Plessa et al., 2010). More specifically, as the rear uppercut (which occurs predominantly in a vertical trajectory) has been shown to generate larger vertical GRF values than straight and hook punches (Chapter 3), an interdependent association may exist between jump squat performance (assessment of lower-body vertical force production) and peak GRF of rear uppercut punches. This may not be the case for other punch types whereby the punching fist acts along the anteroposterior (straights) and mediolateral (hooks) axis, respectively, and suggests how the kinetic chain is perhaps more prevalent in some punch types than others.

The observed links between jump squat performance and peak shoulder angular velocity (in addition to the timing of peak angular velocity) for the lead hook are unique findings that suggest lower-body power influences shoulder joint kinematics during this punch. It is likely this occurs as the force generated by the lower-limbs travels distally through the pelvis, trunk and upper-limbs (i.e. via the kinetic chain) to facilitate the high angular joint velocities at the shoulder during a maximal punch (Cheraghi et al., 2014). On this basis, it is likely that enhancing a boxer's lower-limb P_{max} and RFD will increase the angular velocity magnitudes generated at the shoulder (and potentially the elbow joint) during lead hook punches, and subsequently, the damage potential of this technique. However, the novel finding of a negative association between jump squat performance and delivery time across most punch types indicates the importance of lower-body power in the rapid execution of a maximal punch. Indeed, it appears that the greater the degree of lower-limb power generated at the initiation of a punch, the shorter the time required for the fist to impact the intended target. This seems to underpin the importance of lower-limb force-time characteristics to the execution of high-velocity punches (James et al., 2016a; 2017), with larger lower-limb forces causing a more rapid sequential transfer of energy from the ground distally through the hips and trunk to the fist (Bingul et al., 2017; Cheraghi et al., 2014; Tong-Iam et al., 2017) via rapid lower-limb joint extensions, extension velocities and extensor moments (Chapter 3), resulting in a faster punch delivery time.

Notwithstanding this likely role of lower-body power, at the upper-body (shoulder and elbow) joints the positive associations of the peak angular velocities with bench press throw performance (Pmax) in the three lead hand punches (jab, lead hook, and lead uppercut) reinforce the importance of the musculature surrounding them for generating, storing and then utilising elastic energy (via the SSC) to project the fist towards the target (Cheraghi et al., 2014; Piorkowski et al., 2011). It would therefore appear beneficial for coaches and boxers to adopt upper-body ballistic and/or plyometric exercises (e.g. plyometric push ups, various medicine ball throws, resistance band rows) for the purpose of enhancing upper-limb angular joint velocities during these three punch types.

The finding that peak lead leg GRF was associated with rear hand shot put distance for the three rear hand punches (cross, hook, and uppercut) supports previous literature advocating the importance of lead leg stiffness (i.e. high joint stiffness that minimises knee flexion and the dissipation of GRF) in the transmission of force from the lower limbs to the punching arm via the kinetic chain (Chapter 3; Cheraghi et al., 2014; Turner et al., 2011). Indeed, a rigid lead leg is typified by large vertical, anteroposterior and mediolateral GRF (resultant GRF when combined) which work synergistically to keep the lead leg stable and minimise kinetic energy loss (MacWilliams et al., 1998; McNally et al., 2015). Furthermore, during maximal rear hand punches (i.e. cross, hook, and uppercut), the lead hip, knee and ankle generate smaller peak joint flexion angles (indicative of the lead leg resisting knee flexion and being used as an 'anchor' to provide isometric stability) (Chapter 3). Such factors are imperative to the execution of rear hand punches (Chapter 3) and dynamic full-body movements possessing kinematic similarities to rear hand punches, with lead leg GRF accounting for ~95% of velocity at the point of release in shot putting (McCoy et al., 1984) and exhibiting strong relationships with linear wrist velocity at ball release (R^2 = 0.88 - MacWilliams et al., 1998) and throwing arm acceleration (R^2 = 0.61 - McNally et al., 2015) in baseball pitching. Indeed, these findings highlight the importance of the lower-body, particularly the lead leg, in providing a stable base from which to generate force proximally to the upper limbs during ballistic full-body movements. Therefore, in addition to technical practice, boxers may benefit from the addition of specific training that emphasises force production and stability of the lead leg in their preferred boxing stance (orthodox or southpaw) as a means of enhancing rear hand punch peak fist velocities.

The extent of the associations (moderate to large) between sprinting speed (over 10 and 20 m) and peak rear leg GRF for the rear hand punches is interesting given that sprinting involves both lower- and upper-body actions. While the rear leg exerts larger peak forces compared to the lead leg during a sprint start in order to propel the centre of mass forward (Harland & Steele, 1997; Majumdar & Robergs, 2011; Mero, Kuitunen, Harland, Kyrolainen, & Komi, 2006), the upper-body has been shown to contribute as much as 22% of the body's kinetic energy during a sprint start, which assists velocity through increased propulsion in the direction of movement (Macadam, Cronin, Uthoff, Johnston, & Knicker, 2018; Slawinski et al., 2010). Such overall movement speed will be a ‘performance’ asset owing to the limited time-frame in which a boxer has to execute offensive and defensive strategies (Chang et al., 2011; James, Kelly, & Beckman, 2014). Indeed, indirectly in other combat sports, short-distance sprint performance (≤ 30 m) has been shown to be an important pre-requisite to the execution of techniques among successful judokas, karatekas and taekwondo practitioners (Tabben et al., 2014). Moreover, for movements with similar kinematics to the rear hand cross (baseball pitching), large correlations have also been reported between 10 m sprint times and pitch ball ‘potential energy’ (Nakata, Nagami, Higuchi, Sakamoto, & Kanosue, 2013).

More specific perhaps (with respect to the current rear leg GRF correlations), is the strong link reported between single leg power and short-distance (10-30 m) sprinting performance (Chaouachi et al., 2009; Chelly & Denis, 2001; Lockie, Jalilvand, Callaghan, Jeffriess, & Murphy, 2015). Indeed, velocity at the start of a sprint following the initial ground contact is significantly correlated with rear leg anteroposterior (r = 0.62-0.71) and vertical GRF (r = 0.41-0.50) (Mero, 1988). This is suggested to relate to an athlete’s lower-limb RFD characteristics and concentric muscular power capabilities (Young, Mclean, & Ardagna, 1995), alongside their musculotendinous stiffness during ground contacts which enable an efficient application of GRF (Murphy et al., 2003). Though there is presently a dearth of research concerning the association between movement speed and biomechanical markers of maximal punching, the current findings suggest that as movement speed influences the GRFs exerted during rear hand punches, attempts to improve a boxer’s short-distance speed via resisted sprint drills (with 12-43 % body mass (%BM) as added load; Petrakos, Morin, & Egan,

2006) and plyometrics that emphasise single leg horizontal force production (e.g. single leg broad jumps and bounds; Behrens & Simonson, 2011) and stiffness (e.g. single leg depth jump landings) are likely to yield larger rear leg peak GRFs and subsequently, greater fist velocities and potentially impact forces (Loturco et al., 2016).

5.4.1. Conclusion

This study has established specific physical performance-related qualities are meaningful determinants of the resultant forces and movements occurring during six fundamental punch types among amateur boxers. In particular, (i) upper- and lower-body strength influences peak fist velocity across numerous punch types, (ii) upper-body power is associated with shoulder and elbow joint angular velocities across all lead hand punches and lower-body power with rear uppercut peak lead and rear GRF, (iii) rear hand medicine ball shot put distance is related to peak lead leg GRF of all rear hand punch types and (iv) peak rear leg GRF of all rear hand punches is associated with 10 m and 20 m sprint speed. As the physical qualities assessed within the current study may be augmented through the implementation of specific RT interventions, future research should investigate the influence of such interventions upon maximal punching biomechanics, with the intention of developing comprehensive boxing- and punch-specific strength and conditioning strategies.

Chapter 6

The effects of different resistance training interventions on maximal punch kinetics and kinematics, and performance-related measures among amateur boxers.

Abstract

The purpose of this study was to quantify the effects of two resistance training interventions on measures of muscular strength, power, and three-dimensional (3D) kinetics and kinematics of six punching techniques characteristic of boxing. Fifteen male boxers (age: 27.5 ± 3.4 years, stature: 179 ± 5.5 cm; body mass: 80.1 ± 5.8 kg; years of experience: 9.3 ± 2.3 years) were randomly assigned to either Strength (ST), Contrast (CT) or control (C) groups, with ST and CT performing twice-weekly resistance training sessions over six weeks alongside their regular boxing practice. The C group completed boxing practice only across the same period. All groups performed maximal effort punches against a suspended punch bag during which upper-body kinematics and lower-body kinetics were assessed via 3D motion capture system and two embedded force plates, and physical assessments (back squat 1RM, bench press 1RM, hexagonal-bar deadlift 1RM, jump squat (bodyweight), bench throw (30% bench press 1RM), med-ball shot put (4 kg)) at baseline and post-intervention. Analysis revealed significant 'time' and 'time by group' effects ($P < 0.05$) for all kinetic (peak lead and rear leg GRF, total lead and rear leg impulse) and kinematic variables (delivery time, peak fist velocity, and angular shoulder and elbow joint velocities) across all punch types for both training groups, with CT demonstrating larger pre-to-post performance increases compared to ST (d = 0.2-1.7). Strength performance across all 1RM tests increased moderately from baseline for both training groups ($P <$ 0.05, d = 0.4-1.1), as did jump squat and bench throw maximal power ($P < 0.05$, d = 0.5–0.8), with CT exhibiting larger improvements compared to ST (d = 0.3-0.9). Lead and rear hand shot put incurred small-to-moderate improvements from pre-to-post (P < 0.05) in both CT (d = 0.5-0.8) and ST (d = 0.4) groups. C group did not exhibit any significant changes for any biomechanical, biometric, or physical performance variable from baseline measures. These findings highlight the positive effects of resistance training, especially a CT intervention, upon maximal punching performance, and support its inclusion within boxers' current training practices.

Key words: punching, boxing, contrast training, strength training, biomechanics, GRF, velocity.

Having quantified the importance of certain kinetic and kinematic variables to maximal punching performance (Chapter 3), and the MV associated with these measures

(Chapter 4), research to identify the effects of different RT interventions upon these important variables was justified. Indeed, following the quantification of the associations between maximal punching kinetics and kinematics and measures of muscular strength, power, and speed (Chapter 5), the final study of this thesis investigates how different RT programmes affect biomechanical variables associated with maximal punching, and the physical performance-related qualities that influence it.

6.1. Introduction

RT is a popular form of exercise that has been shown to augment numerous physical and physiological traits, including muscular strength, power, speed, acceleration, hypertrophy, endurance, balance, and coordination (Kraemer & Ratamess, 2004), and subsequently contribute to athletic performance (Suchomel et al., 2016). However, boxing at both amateur and professional levels has typically avoided RT methods, as its coaches and boxers have favoured 'time-honoured' methods, such as high repetition bodyweight/callisthenic exercises alongside technical practice and repeated bouts of aerobic-based training (often to assist with 'making weight' - Bourne et al., 2002; Del Vecchio, 2011; Turner, 2009). This reluctance originates from fears of impairments owing to increased body mass, decreased aerobic capacity, impaired punching velocity and excessive muscle mass (Del Vecchio, 2011; Ebben & Blackhard, 1997). Yet, research has established when performed consistently with appropriate loads, RT can facilitate notable improvements in the biomechanical and physical performance-related characteristics underpinning maximal punching

(Čepulėnas et al., 2011; Del Vecchio et al., 2017; 2019; Hlavačka, 2014; Kim et al., 2018; Markovic et al., 2016; Loturco et al., 2018; Piorkowski et al., 2011).

Čepulėnas et al. (2011) documented how straight punch impact force increased by 44% (jab) and 17% (rear-hand cross) among experienced boxers following a 4-week intervention, while 25-51% (Del Vecchio et al., 2017), 21.4% (Del Vecchio et al., 2019), ~6% (Hlavačka, 2014) and ~27% (Kim et al., 2018) increases in impact power have been reported in straight and hook punches following six-week, nine-week, and sixteen-week RT programmes, respectively. However, no research has yet addressed the effects of RT on the lower-body kinetics (GRFs and impulses) of maximal punching, and only one study has considered its impact upon punch kinematics (Markovic et al., 2016), where increases of 6-11% in jab fist velocity were observed following six-weeks of resistance band training. Given this lack of empirical evidence for the merits of RT on the kinetics and kinematics of all punches fundamental to boxing performance, any attempts to advise coaches and boxers on RT methods would seem incomplete.

Accepting that RT programmes enhance punching performance, identifying the most effective modality for accomplishing this is worthwhile. In non-boxing related research, following on from the established relationships between upper-limb velocity and muscular strength and power measures (Chelly, Hermassi, & Shephard, 2010), both strength (loads ≥ 80% 1RM) and power (loads ≤ 60% 1RM) resistance exercises have been shown to enhance sporting movements possessing kinematic similarities to punching (Hermassi, Chelly, Tabka, Shephard, & Chamari, 2011; Jones et al., 2013; Prokopy et al., 2013; Zaras et al., 2013). More specifically, ST (high load (≥ 80% 1RM) resistance exercises performed on a set-by set basis) have been documented to improve muscular strength and power (Frost, Bronson, Cronin, & Newton, 2016;

Gorostiaga, Granados, Ibanez, & Izquierdo, 2005; Hammami et al., 2017; Suchomel et al., 2016; Zaras et al., 2013) across a number of athletic populations, resulting from augmented neural and mechanical adaptations (Suchomel et al., 2018). Such adaptations include increases in musculotendinous stiffness, motor-unit recruitment and synchronisation, and neural stimulation (Cormie et al., 2011a; Rodríguez-Rosell, Torres-Torrelo, Franco-Márquez, González-Suárez, & González-Badillo, 2019; Suchomel et al., 2016; 2018). In addition, CT (alternated strength and power resistance exercises performed on a set-by-set basis) has been reported to improve measures of muscular strength (Bauer et al., 2019; Fatouros et al., 2000; Rajamohan, Kanagasabai, Krishnaswamy, & Balakrishnan, 2010), muscular power (Alves et al., 2010; Argus, Gill, Keogh, McGuigan, & Hopkins, 2012; de Villarreal et al., 2011; Hammami et al., 2017), and speed (Bauer et al., 2019; Kobal et al., 2017) more than strength or power training performed in isolation, or other RT methods (such as OL, BT, and PT; de Villarreal et al., 2013). Moreover, CT interventions have also been reported to augment sport-specific joint and movement velocities compared to traditional strength-based RT (Hasan, Nuhmani, Kachanathu, & Muaidi, 2018; Hermassi et al., 2011; Ramos Veliz, Requena, Suarez-Arrones, Newton, & de Villarreal, E., 2014). It has been argued that such an advantage exists due to the greater high threshold motor-unit availability (Seitz, de Villarreal, & Haff, 2014; Tillin & Bishop, 2009), increased α-motor neuron excitability (Guillich & Schmidtbleicher, 1996; Trimble & Harp, 1998) and actin-myosin binding rates (Rassier & Macintosh, 2000) that occur following CT. Such neural adaptations are reported to enhance motor skills along the whole force-velocity curve that facilitate optimal training conditions for muscular strength augmentation (Hammani et al., 2017; Rajamohan et al., 2010), neuromuscular power adaptations (Freitas et al., 2017; Spineti et al., 2016) and improvement of force-time characteristics (Granacher et al., 2016; Suchomel et al., 2016; 2018).

Recognising which RT methods are most effective in improving the biomechanical and physical performance-related characteristics of maximal punching is desirable to prepare boxers for the demands of competition and to optimise contest preparation (Chaabene et al., 2015; Loturco et al., 2016; Piorkowski et al., 2011). Accordingly, the aim of this study was to quantify the effects of ST and CT programmes (relative to a control condition) on the ground reaction forces (GRF) and kinematic characteristics of a variety of maximal punches among amateur boxers. It was hypothesised that both training programmes would enhance key biomechanical variables of maximal punching, and that CT would incur larger punch performance increases.

6.2. Methods

6.2.1. Participants

Fifteen males across four weight categories (welterweight (64-69 kg) to heavyweight (81-91 kg)) were recruited from four amateur boxing clubs located across the North West of England, based upon current boxing experience (≥ 2 years) and official bout history (≥ 2 bouts - Table 6.1). A sample size calculation (G*Power version 3.1.9, Universität Düsseldorf, Dusseldorf, Germany - Faul et al., 2009) based on standard input parameters ($\alpha = 0.05$, power = 0.8) and effect size = 0.7 for punch kinetics improvements (gleaned from previous research; Del Vecchio et al., 2019), generated a total sample of nine. All participants provided written informed consent prior to the study and institutional ethical approval was granted by the Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee.

Table 6.1. Biometric and boxing experience characteristics of participants (mean ± SD)

Group*	Age (yrs)	Stature (cm)	Body mass pre (kg)	Body mass post (kg)	Experience (y)
Control (C) (n = 5)	29.6 ± 3.4	179.2 ± 6.2	80.4 ± 5.6	80.6 ± 5.4	10 ± 3.2
Strength training (ST) (n = 5)	25 ± 3.1	178.0 ± 5.7	78.9 ± 7.7	79.5 ± 7.6	8.4 ± 1.5
Contrast training (CT) (n = 5)	28 ± 2.6	179.8 ± 5.7	81.1 ± 4.8	81.7 ± 5.2	9.4 ± 1.8
All groups (n = 15)	27.5 ± 3.4	179 ± 5.5	80.1 ± 5.8	80.6 ± 5.8	9.3 ± 2.3

*Mean differences between groups were not significantly different ($P > 0.05$)

6.2.2. Design

The study adopted a mixed factorial (‘group’ x ‘time’) design in which boxers were randomly allocated to one of three groups (control (C), strength training (ST), and contrast training (CT)). The C group had biomechanical and physical performance-related variables recorded at baseline (week 0) and 7-weeks later and completed no RT (in the form of resistance exercises with external loads (such as free weights)) between baseline and post-intervention measurements. Meanwhile, ST and CT groups completed the same assessments at the same time-points before and after the 6-week RT intervention period (see Figure 6.1). Familiarisation sessions were completed to establish that the boxers could all perform the required assessments.

The C group completed their regular boxing skill and cardiovascular training during the six-week period, while ST and CT groups performed their intervention sessions in place of one regular boxing session and one cardiovascular/endurance training session (which all boxers consistently completed as part of their regular weekly training regimens) each week. No boxers were actively competing (i.e. had a competitive bout scheduled) during the 6-week intervention period. All biomechanical measurements were recorded within the University of Chester’s Biomechanics Laboratory, while all physical performance-related measures were quantified in the Strength and Conditioning Laboratory (Figure 6.1). The dependent variables included 10 biomechanical (four kinematic and six kinetic variables for each of the six punch types) and seven physical performance-related variables (three muscular strength and four muscular power).

6.2.3. Procedures

The first pre-intervention session comprised the biomechanical assessments of six maximal punches (jab, rear-hand cross, lead hook, rear hook, lead uppercut, and rear uppercut). The peak values for punch delivery time, fist velocity, shoulder and elbow angular joint velocities, and GRF (lead and rear leg), in addition to average total impulse (lead leg braking and vertical, rear leg propulsive and vertical) were quantified for each punch type pre and post-intervention. The full biomechanical assessment procedure is described in Chapter 3.

The second testing session comprised various physical assessments to quantify muscular strength and muscular power. Muscular strength was quantified via 1RM tests for the upper-body (bench press (BP)), lower-body (back squat (BS)) and full-body (hexagonal bar deadlift (HBD)). Meanwhile muscular power was measured via bench throws (with 30% bench press 1RM), jump squats (bodyweight), and lead and rear hand shot puts (with 4kg med-ball). A full description of the physical performance-related testing procedures and assessment protocols can be observed in Chapter 5.

Following the baseline biomechanical and physical performance-related assessments, participants were randomly assigned into control (C, n = 5), strength training (ST, n = 5), and contrast training (CT, n = 5) groups. Both ST and CT groups performed twice weekly RT sessions a minimum of 48 hours apart across a six-week period. Each session lasted approximately 80 minutes (including warm up and cool down) and replaced two of the participant’s regular weekly training sessions (resistance, cardiovascular or boxing training). Meanwhile, the C group completed its regular boxing training routine across the same six-week timeframe and were asked to refrain from completing any form of RT outside of commonplace boxing conditioning exercises (e.g. bodyweight push ups, sit ups etc.) during this period.

The ST intervention programme consisted of three resistance exercises per session performed with initial loads of 85% 1RM which were gradually increased over the duration of the intervention (Table 6.2). Meanwhile, the CT group completed six exercises per session, comprising three ‘strength’ (≥ 80% 1RM) and three ‘power’ (bodyweight, band-resisted, or light external load) exercises, respectively (Table 6.3).

Training volume was standardised across both ST and CT groups, wherein they completed a total of four sets per exercise/movement pattern in each session. The ST group performed four sets of each exercise (e.g. back squat), while the CT group performed two sets each of strength (e.g. back squat) and power-based (e.g. jump squat) exercises (four sets total), performed in an alternated sequence (i.e. back squat, jump squat, back squat, jump squat). If a boxer could complete more repetitions than the stipulated repetition range (see Tables 6.3 and 6.4) for a given exercise at a given load, additional load was added (upper-body exercises = 2-4 kg, lower-body exercises = 7-9 kg; McGuigan, 2016) until no more than the stated number of repetitions could be completed.

The exercise selection and 'workload' of each RT intervention (i.e. the ratio of lower- to upper- body exercises) were selected based upon their likelihood of high adherence (i.e. boxers could perform the exercises at a range of locations such as gyms or boxing clubs (if possessing RT equipment)), their relevance to physical-performance assessments (pre- and post-intervention) and potential at enhancing muscular strength (ST and CT) and power qualities (CT). Lower-body exercises were emphasised to a larger degree than upper-body exercises due to associations between lower-body muscular strength and numerous maximal punch kinetic and kinematic variables (Chapter 5). Though the CT group performed a more diverse range of exercises (four upper-body, eight lower-body) than the ST group (two upper-body, four lower-body), total volume was equated/standardised for each movement pattern. Furthermore, training diaries completed over the six-week intervention period suggest boxers performed additional cardiovascular training, circuit training and boxing-specific conditioning sessions alongside the intervention programme (in the case of ST and CT boxes), likely in attempts to maintain their endurance and fighting weight (Bourne et al., 2002; Del Vecchio, 2011). Though boxers were instructed to remove one regular boxing skill/technical session and one cardiovascular/endurance training session each week in order to accommodate for the twice-weekly intervention session, the diversity of each boxer's daily routines and training times (i.e. morning or evening) meant that this was not always fulfilled. The Control group completed an average of five ‘endurance-based’ sessions, four boxing sessions and three ‘circuit training’ sessions per week over the 6-week intervention period. The ST completed an average of two ‘endurance-based’, three boxing and one ‘circuit training’ sessions per week, while the CT completed an average of one (endurance), three (boxing) and two (circuit) sessions weekly. Based upon training diaries provided, endurance-based session were often completed in the morning (by all groups) while boxing sessions (all groups) and intervention session (ST and CT groups) were performed during evenings. Circuit training session were commonly performed at the end of either endurance-based or boxing training sessions.

One-week following the training interventions, the baseline assessments were repeated in order to quantify the influence of the ST and CT training programmes on maximal punching kinetics and kinematics, and maximal muscular strength and peak muscular power. For both ST and CT groups, the overall adherence rate to training (calculated as a percentage of RT sessions completed successfully), was 100% (12 out of 12 sessions) across the six-week intervention period.

6.2.4. Data processing

Kinematic and GRF data were analysed via Qualisys Track Manager (QTM) (version 2.14, Qualisys Inc., Gothenburg, Sweden), whereby reflective markers and anatomical landmarks were labelled. Punch trials were exported to Visual 3D (Version 6, C-Motion Inc., Rockville, United States) from which full-body joint segments and key events were created. From this, upper-limb kinematic and lower-limb GRF and impulse data were calculated. Key events were categorised as: (i) INITIATION and (ii)

CONTACT (see Chapter 3 for a comprehensive description of data processing information).

6.2.5. Statistical analysis

Descriptive statistics (mean ± SD) were generated for all dependent variables and their distributions checked for normality and equal variance via Shapiro-Wilk and Levene tests, respectively, utilising IBM SPSS (version 25, Chicago, USA). As these conditions were met, 2-way (group x time) repeated measures analysis of variance (ANOVA) tests were used to compare mean differences between groups (ST, CT, and C), and across the intervention period (pre and post), with Bonferroni-adjusted *t*-tests adopted as a post-hoc procedure to identify where specific differences existed. A repeated measures analysis of covariance (ANCOVA) was also used to control for baseline mean muscular strength differences between groups (ST, CT, and C), and across the intervention period (pre and post). Cohen's *d* effect sizes and 95% confidence intervals were used to quantify pair-wise comparisons and calculated as: $d = (\bar{x}1 - \bar{x}2) / SD$; where $\bar{x}1$ and $\bar{x}2$ represent the two sample means and SD the pooled standard deviation. The magnitude of Cohen's *d* effect sizes were classified as: trivial < 0.2, small 0.2-0.6, moderate 0.6-1.2, large 1.2-2.0, and very large > 2.0 (Hopkins, 2004). Additionally, the SWC% was calculated from each group's baseline measures to establish the minimum change required to identify 'genuine' differences in performance (Currell & Jeukendreup, 1998) using Cohen's (1988) standardised *d* (0.2 x pooled standard deviation); 'moderate' (MWC%) and 'large' (LWC%) changes were also calculated using three (0.6) and six (1.2) times the SWC% (Batterham & Hopkins, 2006; Hopkins, 2004; Waldron et al., 2013).

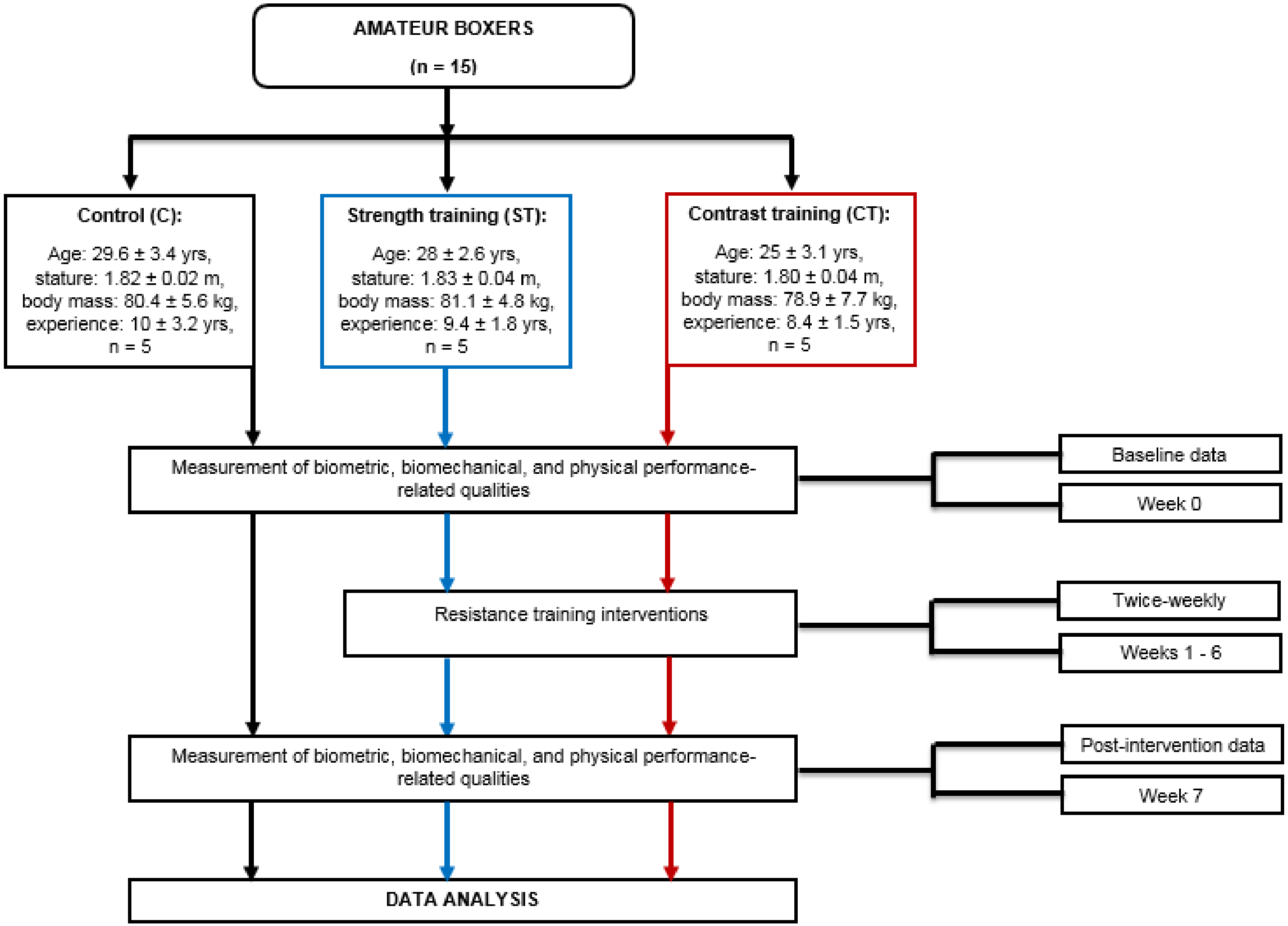

Figure 6.1. Schematic of study design.

Table 6.2. Strength training (ST) group resistance training programme

Period	Weekly session	Exercise	Repetitions	Sets	Load	Rest period
Weeks 1 & 2	Session 1	1. Back squat	4-5	4	85% back squat 1RM	3-5 minutes between sets
		2. Barbell row	4-5	4	85% bench press 1RM	
		3. Hip thrust	4-5	4	85% HBD 1RM	
	Session 2	1. HBD	4-5	4	85% HBD 1RM	
		2. Bench press	4-5	4	85% bench press 1RM	
		3. Barbell split squat	4-5 (per leg)	4	Maximum of 5 repetitions	
Weeks 3 & 4	Session 1	1. Back squat	3-4	4	87.5% back squat 1RM	3-5 minutes between sets
		2. Barbell row	3-4	4	87.5% bench press 1RM	
		3. Hip thrust	3-4	4	87.5% HBD 1RM	
	Session 2	1. HBD	3-4	4	87.5% HBD 1RM	
		2. Bench press	3-4	4	87.5% bench press 1RM	
		3. Barbell split squat	3-4 (per leg)	4	Maximum of 4 repetitions	
Weeks 5 & 6	Session 1	1. Back squat	2-3	4	90% back squat 1RM	3-5 minutes between sets
		2. Barbell row	2-3	4	90% bench press 1RM	
		3. Hip thrust	2-3	4	90% HBD 1RM	
	Session 2	1. HBD	2-3	4	90% HBD 1RM	
		2. Bench press	2-3	4	90% bench press 1RM	
		3. Barbell split squat	2-3 (per leg)	4	Maximum of 3 repetitions	

HBD = hexagonal bar deadlift

Table 6.3. Contrast training (CT) group resistance training programme

Period	Weekly session	Exercise	Repetitions	Sets	Load	Rest period
Weeks 1 & 2	Session 1	1a. Back squat	2-3	2	85% back squat 1RM	3-5 minutes between sets
		1b. CMJ	2-3	2	Bodyweight	
		2a. Barbell row	2-3	2	85% bench press 1RM	
		2b. Med-ball slam	2-3	2	3kg med-ball	
		3a. Hip thrust	2-3	2	85% HBD 1RM	
		3b. Band-resisted broad jump	2-3	2	Bodyweight + 'medium' resistance band (11-36 kg of resistance)	
	Session 2	1a. HBD	2-3	2	85% HBD 1RM	3-5 minutes between sets
		1b. Squat jump	2-3	2	Bodyweight	
		2a. Bench press	2-3	2	85% bench press 1RM	
		2b. ~30° incline ballistic push-up	2-3	2	Bodyweight	
		3a. Barbell split squat	2-3 (per leg)	2	Maximum of 3 repetitions	
		3b. Split squat jump	2-3 (per leg)	2	Bodyweight	
Weeks 3 & 4	Session 1	1a. Back squat	2-3	2	87.5% back squat 1RM	3-5 minutes between sets
		1b. CMJ	2-3	2	Bodyweight + external load equal to 5% body mass	
		2a. Barbell row	2-3	2	87.5% bench press 1RM	
		2b. Med-ball slam	2-3	2	4 kg med-ball	
		3a. Hip thrust	2-3	2	87.5% HBD 1RM	
		3b. Band-resisted broad jump	2-3	2	Bodyweight + 'medium' resistance band (11-36 kg of resistance)	
	Session 2	1a. HBD	2-3	2	87.5% HBD 1RM	3-5 minutes between sets
		1b. Squat jump	2-3	2	Bodyweight + external load equal to 5% body mass	
		2a. Bench press	2-3	2	87.5% bench press 1RM	
		2b. ~15° incline ballistic push-up	2-3	2	Bodyweight	
		3a. Barbell split squat	2-3 (per leg)	2	Maximum of 3 repetitions	
		3b. Split squat jump	2-3 (per leg)	2	Bodyweight + external load equal to 5% body mass	
Weeks 5 & 6	Session 1	1a. Back squat	2-3	2	90% back squat 1RM	3-5 minutes between sets
		1b. CMJ	2-3	2	Bodyweight + external load equal to 10% body mass	
		2a. Barbell row	2-3	2	90% bench press 1RM	
		2a. Med-ball slam	2-3	2	5 kg med-ball	
		3a. Hip thrust	2-3	2	90% HBD 1RM	
		3b. Band-resisted broad jump	2-3	2	Bodyweight + 'medium' resistance band (11-36 kg of resistance)	
	Session 2	1a. HBD	2-3	2	90% HBD 1RM	3-5 minutes between sets
		1b. Squat jump	2-3	2	Bodyweight + external load equal to 10% body mass	
		2a. Bench press	2-3	2	90% bench press 1RM	
		2b. Ballistic push-up	2-3	2	Bodyweight	
		3a. Barbell split squat	2-3 (per leg)	2	Maximum of 3 repetitions	
		3b. Split jump squat	2-3 (per leg)	2	Bodyweight + external load equal to 10% body mass	

HBD = hexagonal-bar deadlift, CMJ = countermovement jump

6.3. Results

6.3.1. Punch kinematics

Both CT (*P* < 0.001, *d* = 0.5-1.8, 10.4-54.6%) and ST (*P* < 0.001, *d* = 0.5-1.7, 7.2-40.9%) groups exhibited moderate-to-large performance increases from pre-to-post across all kinematic variables, while trivial-to-moderate improvements (*P* = 0.082-0.866, *d* = 0.1-0.5, 0.3-7.3%) were noted for C group (see Tables 6.4-6.6). Post-intervention differences for punch delivery time were trivial-to-moderate for all group comparisons (*P* < 0.001, *d* = 0.01-0.8). For the other kinematic variables, large differences were noted between CT and C groups (*P* < 0.001-0.016, *d* = 1.4-1.8), small-to-large differences between ST and C groups (*P* = 0.001-1.000, *d* = 0.3-1.7), and moderate-to-large differences between CT and ST groups (*P* = 0.011-0.589, *d* = 0.6-1.6), respectively. As an example, the pre to post individual changes in rear-hand cross peak fist velocity across all groups can be observed in Figure 6.2.

6.3.2. Punch kinetics

For the six kinetic variables, pre-to-post intervention performance changes were moderate-to-large for CT (*P* < 0.001-0.032, *d* = 0.9–1.9, 14.3-146.1%) and ST groups (*P* < 0.001-0.395, *d* = 0.6–1.8, 11.3-72.3%). Meanwhile, C group exhibited trivial-to-moderate changes (*P* = 0.133-0.880, *d* = 0.03–0.9, 2.2-40.5%) across the majority of variables (Tables 6.4-6.6), but demonstrated large performance increases for peak lead leg GRF across rear-hand cross, lead hook, and rear uppercut punches (*P* = 0.033-0.375, *d* = 1.2-1.5, 14.4-19%) (Appendix 5).

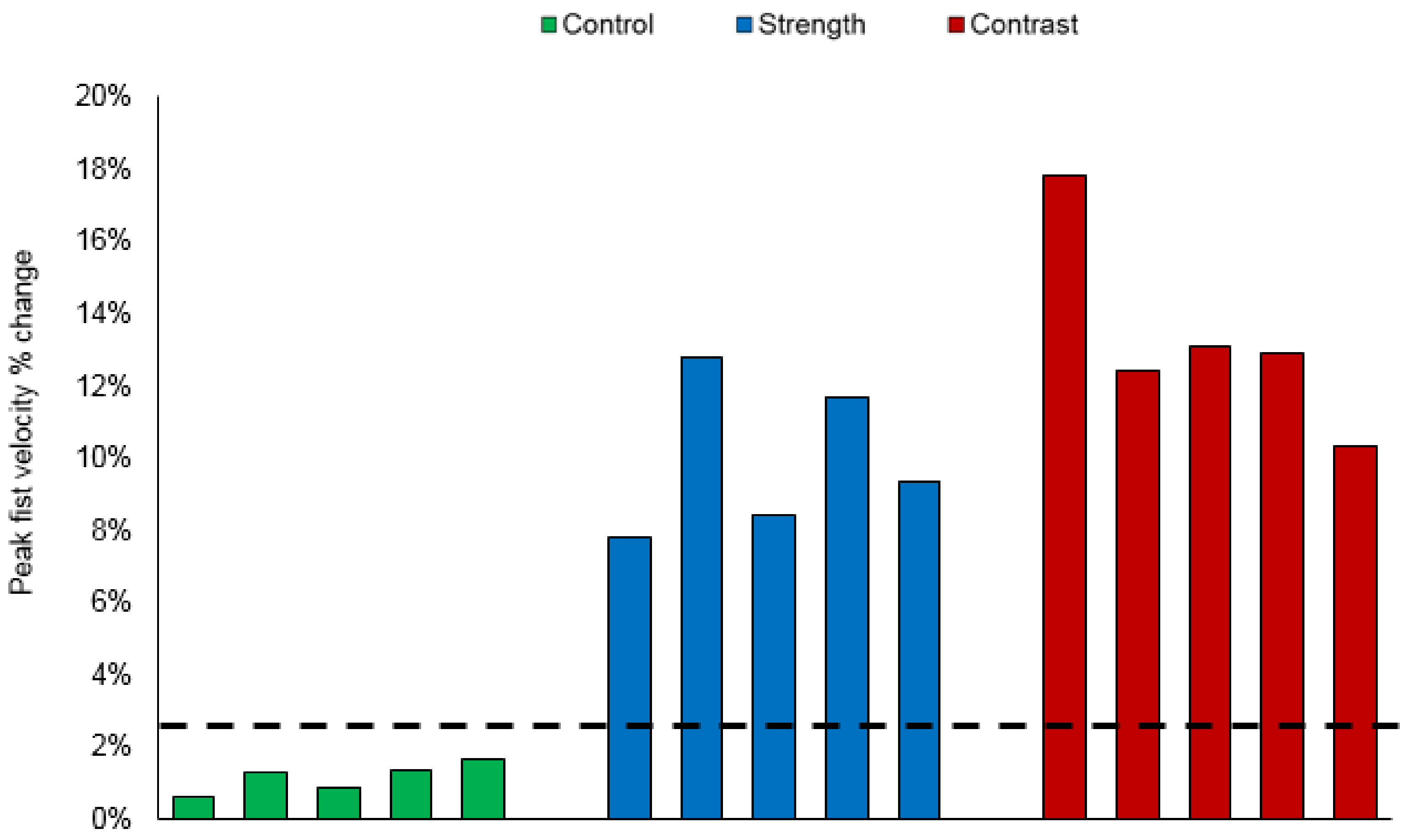

Figure 6.2. Individual percentage changes in peak fist velocity in response to control (C), strength training (ST) and contrast training (CT) interventions. Horizontal line represents the average smallest worthwhile change percentage (SWC%) for baseline rear-hand cross values across all groups.

6.3.3. Physical performance-related variables and body mass

Both CT (*P* < 0.001, *d* = 0.5-1.1, 18.8-22.4%) and ST (*P* < 0.001, *d* = 0.4-1.1, 8.8-15.8%) groups exhibited small-to-large performance improvements from pre-to-post across all strength and power measures. Meanwhile, C group exhibited trivial-to-small performance changes from baseline (*P* = 0.103-1.000, *d* = 0.004-0.2, 0.04-1.9%). Post-intervention differences between CT and C groups were moderate-to-large (*P* = 0.004-0.768, *d* = 0.8-1.4) across the majority of performance tests, as were those between ST and C groups (*P* = 0.067-1.000, *d* = 0.5-1.3), while CT and ST differences were small-to-moderate (*P* = 0.311-1.000, *d* = 0.2-0.8), respectively.

A significant group effect (*P* < 0.001, *F* = 34.0-153.4) was observed for all post-intervention muscular strength measures having controlled for baseline differences, with post-hoc differences also significant between CT and C (*P* < 0.001), ST and C (*P* < 0.001), and CT and ST (*P* < 0.001–0.010) groups, respectively.

From pre-to-post intervention, all groups exhibited trivial body mass increases (*P* < 0.001-0.218, *d* = 0.03-0.14, 0.2-0.9%), while group differences post-intervention were small (*P* = 1.00, *d* = 0.2-0.4 - Table 6.7).

Table 6.4. Control group kinematic and kinetic variable values across punch types from pre-to-post-intervention

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Punch delivery time (ms)	295 ± 31.3	294 ± 29.1	363 ± 45.0	364 ± 42.8	589 ± 85.7	583 ± 86.5	575 ± 72.3	573 ± 70.2	616 ± 75.7	610 ± 76.9	650 ± 81.8	644 ± 82.8
Peak fist velocity (m/s)	5.33 ± 0.33	5.36 ± 0.32	5.72 ± 0.48	5.79 ± 0.47	9.56 ± 0.62	9.61 ± 0.63	9.14 ± 0.86	9.21 ± 0.87	8.28 ± 0.69	8.34 ± 0.66	9.32 ± 1.38	9.36 ± 1.3
Peak shoulder joint angular velocity (deg/s)	548.96 ± 63.84	557.41 ± 620.2	474.81 ± 44.26	509.60 ± 91.61	667.77 ± 91.64	675.46 ± 100.99	680.98 ± 109.84	701.81 ± 91.33	863.61 ± 132.97	879.34 ± 134.67	933.34 ± 95.99	948.35 ± 100.87
Peak elbow joint angular velocity (deg/s)	534.10 ± 79.61	546.78 ± 82.33	266.29 ± 90.98	277.33 ± 96.45	401.91 ± 83.76	417.19 ± 81.02	406.98 ± 97.43	420.45 ± 103.65	400.92 ± 62.19	416.65 ± 64.83	421.11 ± 65.38	429.58 ± 66.46
Peak lead leg GRF (N/kg)	0.40 ± 0.12	0.38 ± 0.12	0.51 ± 0.08	0.60 ± 0.11*	0.71 ± 0.05	0.81 ± 0.07*	0.78 ± 0.09	0.80 ± 0.12	0.73 ± 0.21	0.78 ± 0.12	0.84 ± 0.13	0.96 ± 0.06*
Peak rear leg GRF (N/kg)	0.96 ± 0.17	1.01 ± 0.15	0.87 ± 0.16	0.80 ± 0.05	0.82 ± 0.19	0.80 ± 0.14	0.78 ± 0.17	0.81 ± 0.14	0.93 ± 0.17	0.97 ± 0.15	0.73 ± 0.05	0.75 ± 0.12
Total lead leg net braking impulse (N/s/kg)	-0.80 ± 0.74	-0.89 ± 1.47	-2.98 ± 1.23	-2.98 ± 1.31	-4.50 ± 2.75	-5.78 ± 4.43	-10.45 ± 3.77	-10.92 ± 4.42	-7.80 ± 4.07	-8.30 ± 6.57	-11.59 ± 3.54	-9.43 ± 1.79
Total lead leg vertical impulse (N/s/kg)	14.63 ± 6.71	9.14 ± 5.77	17.91 ± 4.88	19.77 ± 4.99	87.64 ± 35.93	123.12 ± 54.46	78.69 ± 34.26	100.75 ± 53.90	94.17 ± 42.74	126.90 ± 44.61	108.50 ± 60.31	100.12 ± 35.01
Total rear leg net propulsive impulse (N/s/kg)	2.61 ± 0.71	1.97 ± 1.20	5.04 ± 1.81	4.90 ± 1.71	7.56 ± 2.98	6.50 ± 4.56	13.88 ± 3.51	13.05 ± 2.99	10.68 ± 4.28	9.20 ± 5.08	15.24 ± 4.60	11.64 ± 1.65
Total rear leg vertical impulse (N/s/kg)	38.85 ± 12.43	26.36 ± 6.58	42.52 ± 14.57	37.86 ± 11.05	114.85 ± 42.0	107.80 ± 46.55	122.85 ± 42.89	117.40 ± 49.73	121.68 ± 38.38	114.21 ± 34.79	135.67 ± 59.48	101.77 ± 22.78

*denotes significantly different from pre-intervention value at Bonferroni-adjusted P level.

Table 6.5. Strength training group kinematic and kinetic variable values across punch types from pre-to-post-intervention

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Punch delivery time (ms)	386 ± 76.2	347 ± 85.3*	468 ± 83.5	421 ± 89.3*	638 ± 87.8	589 ± 87.4*	623 ± 71.8	574 ± 74.8*	690 ± 35.6	634 ± 37.2*	617 ± 14.6	573 ± 19.5*
Peak fist velocity (m/s)	5.58 ± 0.31	5.97 ± 0.33*[C]	6.01 ± 0.54	6.69 ± 0.38*	10.00 ± 0.33	11.29 ± 0.55*[C,CT]	9.39 ± 0.49	10.46 ± 0.42*[CT]	9.41 ± 1.54	10.61 ± 1.39*[C]	10.02 ± 0.94	11.30 ± 1.35*
Peak shoulder joint angular velocity (deg/s)	587.91 ± 43.87	648.52 ± 39.55*	506.32 ± 94.65	636.42 ± 152.98*	601.28 ± 51.96	767.70 ± 117.90*	717.86 ± 58.36	908.45 ± 65.83*[C,CT]	912.81 ± 71.76	1109.69 ± 92.62*[C]	956.15 ± 45.80	1120.87 ± 71.3*[C]
Peak elbow joint angular velocity (deg/s)	467.60 ± 53.3	569.11 ± 56.21*[CT]	306.86 ± 89.20	378.70 ± 89.68*	423.73 ± 34.86	541.36 ± 33.73*[C]	484.38 ± 54.39	608.48 ± 63.61*[C]	452.75 ± 64.22	638.05 ± 56.85*[C]	413.82 ± 84.49	568.72 ± 118.49*
Peak lead leg GRF (N/kg)	0.40 ± 0.09	0.49 ± 0.16	0.65 ± 0.15	0.96 ± 0.28*[C,CT]	0.80 ± 0.14	0.89 ± 0.18*	0.83 ± 0.08	1.16 ± 0.23*[C,CT]	0.85 ± 0.16	1.15 ± 0.20*[C]	1.05 ± 0.27	1.48 ± 0.41*[C]
Peak rear leg GRF (N/kg)	0.98 ± 0.17	1.40 ± 0.29*	0.87 ± 0.14	0.97 ± 0.18	0.90 ± 0.18	1.20 ± 0.24*	0.82 ± 0.13	0.92 ± 0.11	0.96 ± 0.24	1.22 ± 0.17*[CT]	0.75 ± 0.13	0.95 ± 0.24*
Total lead leg net braking impulse (N/s/kg)	-0.52 ± 0.65	-1.20 ± 0.38*	-3.34 ± 2.11	-3.89 ± 1.80	-4.41 ± 5.08	-6.94 ± 3.10*[C]	-6.65 ± 3.06	-9.67 ± 4.51*	-2.54 ± 1.63	-10.09 ± 4.58*[C]	-7.04 ± 3.66	-8.97 ± 3.26
Total lead leg vertical impulse (N/s/kg)	5.19 ± 3.81	18.05 ± 5.89	11.04 ± 4.20	22.77 ± 5.74[C]	43.98 ± 19.38	102.64 ± 49.08*[C]	27.91 ± 9.37	74.30 ± 36.71*[C]	47.03 ± 16.07	133.95 ± 42.40*[C]	41.80 ± 18.05	73.88 ± 15.96[C]
Total rear leg net propulsive impulse (N/s/kg)	1.05 ± 0.88	2.59 ± 0.79*	2.94 ± 1.53	6.52 ± 3.38*	3.12 ± 1.11	8.71 ± 2.49*	7.99 ± 3.97	13.29 ± 6.58*[C]	2.79 ± 1.87	11.05 ± 3.32*[C]	6.87 ± 4.12	11.52 ± 4.88*[C]
Total rear leg vertical impulse (N/s/kg)	21.78 ± 12.67	37.87 ± 16.92*	13.94 ± 3.8	50.35 ± 22.76*[C]	50.41 ± 18.25	108.27 ± 50.01*	42.50 ± 19.08	111.33 ± 57.24*	47.62 ± 16.03	126.34 ± 38.91*	33.83 ± 23.04	92.86 ± 35.36*

*denotes significantly different from pre-intervention value at Bonferroni-adjusted P level.
[C] = significantly different than control group ($P < 0.05$).
[CT] = significantly different than contrast training group ($P < 0.05$).

Table 6.6. Contrast training group kinematic and kinetic variable values across punch types from pre-to-post-intervention

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Punch delivery time (ms)	379 ± 58.8	318 ± 52.6*	484 ± 95.9	420 ± 91.2*	640 ± 108.1	569 ± 107.6*	586 ± 142.2	522 ± 143.7*	633 ± 107.1	568 ± 102.6*	570 ± 123.3	505 ± 119.6*
Peak fist velocity (m/s)	5.38 ± 0.45	6.31 ± 0.37*^{C}	6.59 ± 0.81	7.45 ± 0.79*^{C}	11.45 ± 1.30	13.24 ± 0.83*^{C,ST}	10.71 ± 0.93	11.91 ± 0.91*^{C,ST}	10.62 ± 1.36	12.17 ± 1.39*^{C}	11.22 ± 1.77	12.64 ± 1.52*^{C}
Peak shoulder joint angular velocity (deg/s)	615.33 ± 96.38	706.63 ± 95.02*	495.99 ± 41.82	707.09 ± 90.54*	770.70 ± 150.85	985.38 ± 151.57*	867.04 ± 161.92	1196.33 ± 133.63*	974.77 ± 86.11	1228.50 ± 92.80*	1045.25 ± 98.64	1263.80 ± 74.90*
Peak elbow joint angular velocity (deg/s)	605.93 ± 113.84	786.32 ± 131.18*^{C,ST}	343.71 ± 98.22	478.02 ± 74.18*^{C}	381.80 ± 50.10	590.18 ± 42.97*^{C}	511.97 ± 85.60	717.65 ± 83.59*^{C}	479.60 ± 106.45	737.57 ± 74.73*^{C}	471.84 ± 95.78	696.32 ± 87.91*^{C}
Peak lead leg GRF (N/kg)	0.48 ± 0.16	0.68 ± 0.27*	0.60 ± 0.14	1.47 ± 0.11*^{C,ST}	0.79 ± 0.17	1.03 ± 0.10*^{C}	0.81 ± 0.10	1.44 ± 0.15*^{C,ST}	0.86 ± 0.16	1.23 ± 0.11*^{C}	0.98 ± 0.16	1.69 ± 0.23*^{C}
Peak rear leg GRF (N/kg)	0.91 ± 0.12	1.59 ± 0.25*^{C}	0.87 ± 0.17	1.12 ± 0.25*	0.86 ± 0.11	1.52 ± 0.37*^{C}	0.86 ± 0.12	0.98 ± 0.15*^{C}	1.01 ± 0.17	1.51 ± 0.23*^{C,ST}	0.78 ± 0.19	1.18 ± 0.17*^{C}
Total lead leg net braking impulse (N/s/kg)	-1.28 ± 0.38	-1.47 ± 1.12*^{C}	-4.29 ± 1.09	-5.14 ± 2.95	-2.80 ± 1.00	-4.99 ± 3.02*^{C}	-8.24 ± 0.75	-10.96 ± 3.01*	-2.69 ± 0.72	-6.55 ± 4.17*^{C}	-7.18 ± 1.14	-10.17 ± 1.22*
Total lead leg vertical impulse (N/s/kg)	5.37 ± 2.32	22.73 ± 16.45*	13.82 ± 2.30	33.71 ± 30*	58.31 ± 7.67	113.67 ± 43.24*^{C}	30.81 ± 3.49	85.54 ± 58.77*^{C}	34.95 ± 4.92	115.13 ± 33.05*^{C}	36.35 ± 3.95	93.12 ± 35.55*^{C}
Total rear leg net propulsive impulse (N/s/kg)	0.32 ± 0.48	1.91 ± 0.61*^{C}	3.18 ± 1.61	8.05 ± 4.04*	1.40 ± 0.30	7.88 ± 5.30*^{C}	8.26 ± 0.94	13.45 ± 2.83*	1.39 ± 0.56	9.08 ± 5.09*^{C}	6.55 ± 0.99	11.44 ± 1.73*^{C}
Total rear leg vertical impulse (N/s/kg)	16.03 ± 3.02	37.81 ± 9.93*	11.64 ± 7.68	64.41 ± 36.65*^{C}	37.75 ± 3.33	128.9 ± 50.01*^{C}	32.35 ± 6.47	105.46 ± 47.18*^{C}	40.88 ± 4.08	123.26 ± 52.80*^{C}	27.11 ± 4.06	95.92 ± 31.48*^{C}

*denotes significantly different from pre-intervention value at Bonferroni-adjusted P level.
^{C} = significantly different than control group ($P < 0.05$).
ST = significantly different than strength training group ($P < 0.05$).

Table 6.7. Physical performance-related and body mass values from pre-to-post-intervention

Variable	Control group			Strength group			Contrast group		
	Pre	**Post**	**%change**	**Pre**	**Post**	**%change**	**Pre**	**Post**	**%change**
Back squat 1RM (kg)	102.0 ± 9.1	101.5 ± 8.9	-0.5	102.5 ± 2	116.5 ± 17.3*^{M}	+13.7	109.5 ± 24.9	134.0 ± 24.5*^{L}	+22.4
Back squat 1RM ($kg \cdot M_b^{-0.67}$)	5.4 ± 0.3	5.4 ± 0.3	-0.6	5.5 ± 0.8	6.2 ± 0.6*^{L}	+13.2	5.7 ± 1.1	7.0 ± 1.0*^{L}	+21.9
Bench press 1RM (kg)	97.0 ± 9.1	97.5 ± 8.5	+0.5	102.0 ± 21.5	111 ± 20.2*^{M}	+8.8	101.0 ± 21	120.1 ± 23.7*^{L}	+15.8
Bench press 1RM ($kg \cdot M_b^{-0.67}$)	5.1 ± 0.3	5.1 ± 0.3	+0.4	5.4 ± 0.9	5.9 ± 0.8*^{M}	+8.4	5.3 ± 0.9	6.3 ± 1.0*$^{M-L}$	+18.3
HBD 1RM (kg)	130.5 ± 8.6	131 ± 7.2	+0.4	132.5 ± 15.6	153.5 ± 16.6*^{L}	+15.8	139.5 ± 26.2	173.50 ± 25.9*^{L}	+22.2
HBD 1RM ($kg \cdot M_b^{-0.67}$)	6.9 ± 0.4	6.9 ± 0.4	+0.2	7.1 ± 0.5	8.2 ± 0.4*^{L}	+15.2	7.3 ± 1.1	8.9 ± 1.2*^{L}	+21.6
Jump squat P_{max} (W/kg)	56.3 ± 4.9	56.3 ± 4.9	-0.0	55.0 ± 8.9	60.1 ± 8.8*^{S}	+9.3	53.6 ± 9.1	63.6 ± 9.2*^{M}	+18.8
Bench throw P_{max} (W/kg)	5.5 ± 0.7	5.6 ± 0.7	+0.2	5.4 ± 1.0	6.01 ± 1.1*^{S}	+11.6	5.3 ± 1.2	6.3 ± 1.1*^{M}	+20.1
Shot put (m) (lead hand)	9.03 ± 0.46	9.04 ± 0.48	+0.0	9.49 ± 1.54	10.11 ± 1.54*^{M}	+6.6	9.45 ± 1.2	10.51 ± 1.24*$^{M-L}$	+11.2
Shot put (m) (rear hand)	10.03 ± 0.41	10.22 ± 0.4	+1.9	11.26 ± 1.93	12.07 ± 2.1*^{M}	+6.2	11.27 ± 2.26	12.38 ± 2.3*^{M}	+9.9
Body mass (kg)	80.4 ± 5.6	80.6 ± 5.4	+0.2	78.9 ± 7.7	79.5 ± 7.6*^{S}	+0.9	81.1 ± 4.8	81.7 ± 5.2*^{S}	+0.8

*denotes significantly different from pre-intervention value at Bonferroni-adjusted *P* level.
^{T}denotes trivial effect relative to C group.
^{S}denotes small effect relative to C group.
^{M}denotes moderate effect relative to C group.
^{L}denotes large effect relative to C group.
$kg \cdot M_b^{-0.67}$ = kg body mass to the power 0.67.

6.4. Discussion

This study has established that ST and CT programmes performed alongside regular boxing practice enhance biomechanical and physical performance-related characteristics associated with the six fundamental punch types, with the CT programme yielding superior effects to the ST programme. These novel findings suggest coaches and boxers should consider implementing such RT methods within their current training practice to augment many of the qualities associated with successful boxing performance.

6.4.1. Punch kinematics

The moderate-to-large decreases in punch delivery time from baseline to post-intervention measures across all punch types for both ST and CT groups indicate that high-force and combined high-force and velocity RT can significantly decrease the time taken to execute a maximal punch, regardless of punch technique (i.e. straight, hook, or uppercut). The delivery time improvements of 7.2-10.1% in the ST group exceeded the SWC% values (2.9-4.2% - see Appendix 5) required to have a 'meaningful' effect on performance across all punches. Meanwhile, CT group performance increases (10.4-16%) surpassed the MWC% values (7.4-12.5%) for each punch type, signifying CT was more effective than ST at decreasing punch delivery times. These findings are noteworthy given the reliance of successful boxing outcome on the speed of technique execution, with rapidly delivered strikes affording an opponent less time to defend/evade (Verkhoshansky & Siff, 2009) and potentially increasing the 'knock-out potential' of a punch (La Bounty et al., 2011). Thus, given the importance of delivery time to maximal punching (Chapter 3), and its relationships with muscular strength, power, and speed performance variables (Chapter 5), the ST and CT group delivery time decreases signify the efficacy of such RT interventions in the enhancement of this key maximal punching kinematic characteristic.

Enhancements in peak fist velocity across all punch types by ST (7.1-12.9%) and CT (12.7-17.2%) groups also reflect the positive influence of both high-load and combined high-load, high-velocity RT on this characteristic. Indeed, for both training groups, peak fist velocity improvements were larger than the MWC% values (5.4-11.3%) across all punch types, while the CT group also exhibited jab and lead hook improvements larger than LWC% values (jab = 8.3%, lead hook = 13.4% - Appendix 5). Only jab fist velocities have been examined previously, with performance improvements of 6-11% reported following six-weeks of resistance band training (Markovic et al., 2016) being comparable with the ST group for the jab (10.9%), but less than the CT group (13%). Though the different intervention methods between studies renders comparisons difficult, the results of both emphasise jab peak fist velocity can be enhanced via RT, with the individual boxer responses to the ST and CT interventions in the current study adding further credibility to this notion (see Appendix 6). Given the jab is the most frequently executed punch within competition (Davis et al., 2017; Thomson & Lamb, 2016), increasing its velocity via ST or CT interventions could improve its effectiveness (‘damage potential’ from augmented forces) and thereby overall boxing performance. This is based upon the impulse-momentum relationship whereby an increase in fist velocity yields an increase in momentum (mass x velocity), and consequently, more force being imparted upon impact (impulse = force x time; Turner et al., 2011). Complimentary benefits may emerge via the large increases in fist velocity of the other punches (rear-hand cross, lead and rear hooks and uppercuts) from pre-to-post following ST (11.3-12.9%) and

CT (11.2-15.5%) RT. Coaches and boxers should therefore take note of these findings and consider adopting ST or CT programmes alongside their technical practice to enhance these characteristics of punches.

With respect to the observed improvements in peak angular joint velocities (shoulder and elbow) across all punches (apart from the rear-hand cross) following RT, no comparable boxing or combat sport-related findings exist. Some research among sports possessing kinematic similarities with punching has documented improvements in throwing and upper-limb joint velocity in water polo (Ramos Veliz et al., 2014), handball (Hermassi et al., 2011; Hoff & Almåsbakk, 1995), Basketball (Hasan et al., 2018), softball (Prokopy et al. 2008), and baseball (Palmer et al., 2015) players following upper-body RT. Indeed, as upper-body strength and power are associated with the angular shoulder and elbow velocities of different punches (Chapter 5), the angular joint velocity improvements across ST (10.3-40.9%) and CT (14.8-53.8%) groups are a result of the augmented upper-body muscular strength and power among the current boxers. Though both training interventions were effective at enhancing these variables ‘meaningfully’, CT yielded larger peak shoulder and elbow angular joint velocity increases than ST alone, supporting the hypothesis CT is more effective than ST at increasing maximal punch kinematics. Subsequently, coaches and boxers should consider implementing either training programme to strengthen the upper-extremity movement patterns and joint motions associated with different punches (e.g. shoulder adduction, abduction, flexion and extension, and elbow flexion and extension - Cabral et al., 2010; Piorkowski et al., 2011).

It is noteworthy that the CT intervention yielded larger increases only in peak angular shoulder (rear hook) and elbow (jab) joint velocities than the ST. While this is difficult to explain, it is possibly due to the power/ballistic exercises within the CT group. Previous research has suggested the combination of heavy RT and high-velocity movements in the same session is an effective strategy for enhancing intra- and inter-muscular coordination that effectively translates into augmented functional performance (Cronin, McNair, & Marshall, 2002). It seems therefore mimicking the high lower-limb forces and upper-limb velocities associated with maximal punching (Chapter 3; Piorkowski et al., 2011) via combined strength and power resistance exercises (e.g. CT group) can generate increased upper-extremity function at high-velocities, greater RFD, and overall athletic performance (Davies et al., 2015; Swanik et al., 2016).

6.4.2. Punch kinetics

Though the effects of RT on the impact kinetics of maximal punching, such as force (Čepulėnas et al., 2011) and power (Del Vecchio et al., 2017; 2019; Hlavačka, 2014; Kim et al., 2018) have been reported, no research has investigated its effects upon lower-body kinetics. The large and moderate-to-large post-intervention GRF and impulse differences (lead and rear legs) between groups (e.g. lead leg GRF - ST = 11.6-47.1%, CT = 30.3-146.1%) illustrate CT is more effective at enhancing these kinetic variables than ST alone. Indeed, lead leg kinetics are crucial in minimising kinetic energy loss (Yan-ju et al., 2013), while rear leg kinetics are responsible for the generation of kinetic energy (Cheraghi et al., 2014). These variables subsequently amalgamate to transmit force from the lower limbs to the arm/hand segments via sequential joint extension angles, angular extension velocities and extensor moments (Chapter 3; Cheraghi et al., 2014; Lenetsky et al., in press; Turner et al., 2011). With regards to these kinetic variables, it appears the larger lead leg GRF and braking impulses documented for the CT group are due to the addition of ballistic/plyometric exercises to this training modality, as well potential improvements in lead hip, knee and ankle extension angles, angular extension velocities and extensor moments, respectively (Chapter 3). Such resistance exercises have been reported to increase lower-limb musculotendinous stiffness, force absorption capabilities and force-time characteristics (Davies et al., 2015; Fouré et al., 2011; Kubo et al., 2007) to a greater extent than heavy ST alone. Indeed, the improvements in peak lead leg GRF for CT group compared to ST group in the current study corroborate the results of previous research. Moreover, the increases in upper-limb joint angular velocities (shoulder and elbow) and peak fist velocities potentially suggest that improving this kinetic variable may have improved the lead leg's ability to resist unwanted knee flexion and provide isometric stability that permitted the rear leg to generate kinetic energy that was successfully transferred to the upper-extremities (Cabral et al., 2010; Chapter 3; Cheraghi et al., 2014; Lenetsky et al., 2019; Turner et al., 2011). Indeed, the significant increases in peak rear leg GRF exhibited by the CT group likely improved a boxer's ability to generate greater peak rear ankle, knee and hip extension angles, angular extension velocities and extensor moments that assisted in the transmission of momentum to the upper-extremities (Chapter 3).

Consequently, the magnitude of performance improvements for the CT group (see Appendices 4 and 5) supports its inclusion as part of boxer's contest preparation in order to enhance lead and rear leg kinetics across all punches. Indeed, in addition to technical practice, it is recommended boxers implement specific training that enhances force production and stability of the lead leg as a means of potentially enhancing rear hand punch peak fist velocities via an increase in lead leg GRF and impulse alongside peak ankle, knee and hip joint extension angles, angular extension velocities and extensor moments (Chapter 3). Increasing the force generating capabilities of the rear leg via specific training that strengthen lower-limb joint extensions and enhance extension velocities, GRF and impulse are also recommended as a means of augmenting peak fist velocities (Chapter 5).

6.4.3. Physical performance-related variables

The observed CT group back squat and bench press 1RM increases were superior to those of Kim et al. (2018), who reported 16.3% (back squat) and 18% (bench press) improvements following a 16-week ‘boxing-specific’ RT programme. Again, this likely stems from the loading parameter differences between studies, whereby boxers in Kim et al. (2018) performed traditional (e.g. barbell back squat) and boxing specific (e.g. resistance band punches) exercises in a circuit fashion, compared to the heavy, strength enhancing loads (~85-90% 1RM) in the current study. These results suggest a CT intervention that alternates heavy resistance exercises (e.g. bench press at 90% 1RM) with a power exercise sharing similar kinematics (e.g. bench throw, ballistic push-up) is the more effective means of increasing muscular strength in amateur boxers. This is likely due to the neural and mechanical adaptations associated with CT, such as increased type IIX muscle fibre recruitment, agonist muscle neural drive, α-motor neuron excitability (via H-reflex changes), maximal cross-bridge cycle transition rate, and muscle tendon unit (MTU) stiffness (Aagaard et al., 1985; 2002; Bernardi et al., 1996; Cormie et al., 2011a; Guillich et al., 1996; Hammani et al., 2017; Tillin et al., 2012; Trimble & Harp, 1996).

Previous research has reported increases in type IIA myosin heavy chain isoform percentages (Liu, Schlumberger, Wirth, Schmidtbleicher, & Steinacker, 2003;

Perez-Gomez et al., 2008) following ST, while power training preserves, and potentially increases, the percentage of type IIX muscle fibres (Bottinelli, Canepari, Pellegrino, & Reggiani, 1996; Harridge et al., 1996). Meanwhile, combined strength and power training (such as CT) preserves type IIX muscle fibre proportion, as power training either in the same session or on alternate days to ST minimises the shift to type IIA (Stasinaki et al., 2015). This type IIX muscle fibre preservation is beneficial for muscular power production as these fibres generate more forceful contraction velocities, power, and rate of tension than type IIA, type IIB and type I fibres, respectively (Bottinelli et al., 1996; Harridge et al., 1996; Stasinaki et al., 2015). Furthermore, type IIX fibres possess the greatest cross-bridge cycling rate of all muscle fibres which influence early contraction phase RFD and agonist muscle neural drive (Aagaard et al., 2002; Andersen & Aagaard, 2006; Oliveira, Oliveira, Rizatto, & Denadai, 2013; Tillin et al., 2012). Indeed, changes in early contraction phase RFD are related (r = 0.61) with changes in type IIX muscle fibre percentages following an RT intervention (Andersen et al., 2010), meaning high force can be applied rapidly at the onset (~50 ms) of a dynamic movement/motion (e.g. the initiation of a maximal punch). In addition, improvements in MTU stiffness (19-34% reported in previous research following 4 to 6-week RT interventions - Kubo, Kanehisa, & Fukunaga, 2002; Tillin et al., 2012) may have also occurred among the current study's participants given their exposure to high-force (ST and CT) and high-velocity (CT) resistance exercises (Cormie et al., 2011a). Subsequently, an increase and/or maintenance in type IIX muscle fibre proportion alongside augmented MTU stiffness may have occurred to a larger degree in the CT group due to these boxers increasing their ability to produce both explosive and maximal muscular force as opposed to maximal force alone (Stasinaki et al., 2015).

Increases in neural drive of ST and CT boxers are also suggested to have occurred following the RT interventions. Previous research has reported how increases in agonist neural drive account for up to 30% of muscular strength adaptations following short-term RT interventions (≤12-weeks) (Balshaw et al., 2017). Moreover, high-load RT (80% 1RM) results in significantly greater neural drive adaptations than low-load RT (30% 1RM) that account for the disparate increases in muscle strength observed between such training loads (Jenkins et al., 2017). Neuromuscular mechanisms that influence neural drive include contractile RFD, motoneuron recruitment, discharge rate and firing frequency, incidence of discharge doublets and sarcoplasmic reticulum Ca^{2} kinetics changes, all of which are enhanced following periods of RT (Aagaard et al., 2002; Gabriel et al., 2006). Improvements in contractile RFD following RT have been evidenced by increases in peak RFD, MVC, EMG signal amplitude and rate of EMG rise (Aagaard et al., 2000; 2002; Häkkinen et al., 1985; 1998; Narici, Roig, Landomi, Minetti, & Cerretelli, 1989; van Cutsem et al., 1998). Meanwhile, motoneuron recruitment, discharge rate and firing frequency increases of 15-49% have been reported following 6-weeks of RT (Kamen & Knight, 2004), which are suggested to influence the magnitude of contractile fibre tensions (Aagaard et al., 2002; Gabriel et al., 2006), that also reduce the neural cost of contractions (lower activation required to produce the same absolute torque) following RT (Jenkins et al., 2017). Consequently, though such mechanisms were not analysed in the current study, it seems likely that the performance increases exhibited by ST and CT groups were the consequence of augmented neural drive and related neural responses resulting from RT. In addition, previous research has reported a sixfold increase (5% to 33%) in occurrence of discharge doublets (firing pattern of individual motor units) following ballistic/explosive-type RT (van Cutsem et al., 1998). Such changes enhance the maximal contraction force and tension capabilities of the trained muscle(s) and muscle contraction force by increasing sarcoplasmic reticulum binding rates (Jones et al., 2013) that take advantage of the ‘catch-like’ properties of skeletal muscle (Aagaard, 2003; Gruber & Gollhofer, 2004). Therefore, it is reasonable to suggest that such changes in neural mechanisms may explain why the CT group exhibited greater muscular strength and power improvements than the ST group. Indeed, the additional ‘contrasting’ (i.e. ballistic/explosive) exercises the CT group completed may have promoted adaptations across a greater range of neural qualities. Although, it should be stated that the scale of both neural and morphological adaptations during early phase resistance training programmes are still somewhat equivocal (Enright, Morton, Iga, & Drust, 2015). Thus, future research is recommended to quantify the changes in such characteristics during and following ST and CT programmes in conjunction with regular boxing training.

Whilst neural and mechanical adaptations are key components of strength and power improvements during and following RT, morphological characteristics (i.e. fascicle length; fascicle angle of pennation) also influence early adaptations to RT (Cormie et al., 2011a; Blazevich, 2006) and the force generating capacity of musculature (Seynnes et al. 2007). Increases in fascicle length (Lf - fascicular path between the insertions of the fascicle onto the upper and deeper aponeurosis (Stasinaki et al., 2015) permit a muscle to contract more rapidly and generate greater peak power at higher velocities, while decreases in length facilitate larger peak force generation capabilities (Wilson & Lichtwark, 2011). Previous research has reported increases in the fascicle length of quadricep musculature after 4-weeks (4.8% - Tillin et al., 2012), 5-weeks (9.9% - Seynes et al., 2007), and 6-weeks of ST (2.1% - Stasinaki et al., 2015), respectively. Such fascicle length adaptations are suggested to occur as a result of a serial increase in sarcomere addition, both in series and in parallel (Wickiewicz, Roy, Powell, & Edgerton, 1983), in addition to larger ranges of movement (Blazevich, Gill, & Zhou, 2006) and increased hypertrophy (muscle thickness and cross-sectional area - Farup et al., 2012). In contrast, adaptations to CT include decreases in fascicle length of the vastus lateralis (-7%) and gastrocnemius (-11.8%), respectively, after 6-weeks (Stasinaki et al., 2015). The authors suggested that the decrease in fascicle length following CT occurred due to an increase in strength-to-body mass ratio, supported by the muscular strength increases (18.4–35.6%) without notable changes in sarcomere addition, muscle thickness, fibre cross sectional area (i.e. hypertrophy) or body mass (Stasinaki et al., 2015). Given that shorter fibre lengths can generate greater peak forces (Wilson et al., 2011), and if combined with high-velocity actions/exercises, can reduce their shortening velocities (Wakeling, Blake, Wong, Rana, & Lee, 2011), these findings along with those of the current study appear to suggest that CT is an effective RT method for boxers aiming to enhance muscular strength, power and architectural characteristics without the addition of unwanted hypertrophy or body mass increases.

In addition to fascicle length, the fascicle angle of pennation (θ_p) (the angle between the muscle's fascicles and the line of action – Cormie et al., 2011a) is another architectural characteristic affected by RT. Increases of 7–34% in this variable have been reported following RT interventions ranging from 5 to 16-weeks (Aagaard et al., 2001; Blazevich et al., 2007; Blazevich, Gill, Bronks, & Newton, 2003; Enright et al., 2015; Faup et al., 2012; Seynnes, de Boer, & Narici, 2007). An increase of 29% has also been documented for the triceps brachii following 16-weeks of RT (Kawakami, Abe, Kuno, & Fukunaga, 1995). More specific to the current study, Stasinaki et al. (2015) reported how CT increased vastus lateralis (19.9%) and gastrocnemius

(14.3%) fascicle angles after a 6-week intervention, while ST increased the same variables to a larger degree (vastus lateralis = 26.1%, gastrocnemius = 5.3%). Increases in fascicle angles of pennation enable more contractile material to attach to the aponeurosis, leading to increased muscular force output (Erskine, Fletcher, & Folland, 2014). Moreover, it is also indicative of muscle architecture remodelling through the addition of sarcomeres in series (myofibrils), which in turn, suggest an increase in muscular hypertrophy at the macroscopic level (Blazevich et al., 2003; Seynnes et al., 2007). This implies that the ST group in the current study may have achieved greater muscular hypertrophy adaptations than the CT group, but not muscular strength or power.

Indeed, Granacher et al. (2016) established that CT resulted in greater power and RFD performance changes compared with other RT methods (including ST). Though ST generates increases in maximal muscular strength and power by targeting the force component of the power equation (force x velocity) (Cormie et al., 2011b, Deschenes & Kraemer, 2002), the ability to apply force at high velocities may be hindered if excessive emphasis is placed upon high load, low-velocity movements (Cormie et al., 2011b; Freitas, Martinez-Rodriguez, Calleja-Gonzalez, & Alcaraz, 2017). Meanwhile, though ballistic/plyometric exercises are reported to enhance maximal muscular power production (Cormie et al., 2011b; Markovic & Mikulic, 2010), jump performance (García-Pinillos, Martínez-Amat, Hita-Contreras, Martínez-López, & Latorre-Román, 2014, Baker, 1996; Markovic & Mikulic, 2010) and sprint performance (Bolger, Lyons, Harrison, & Kenny, 2015; García-Pinillos et al., 2014; Rumpf, Lockie, Cronin, & Jalilvand, 2016), such performance increases may also plateau if muscular strength is not increased concurrently based on the linear relationship between force and power production (Cormie et al., 2011a).

Consequently, CT has been suggested to generate larger jump and sprint performance increases compared to strength, power or speed training alone (Argus et al., 2012; de Villarreal et al., 2013; Fatouros et al., 2000) due to this training modality enhancing motor skills along the whole force-velocity curve, and subsequently, producing optimal training conditions for neuromuscular power adaptations (Ebben & Watts, 1998; Freitas et al., 2017) and improvement of force-time characteristics that can be effectively transferred to athletic activities (Suchomel et al., 2016; 2018). Indeed, CT has augmented lower-body power performance greater than traditional RT (such as ST) and control interventions (d = 1.3-1.5; Pagaduan et al., 2019). Moreover, CT has been shown to increased CMJ height and flight time and repeated short sprint ability (RSSA) greater than ST (Spineti et al., 2016), with the authors suggesting CT is the optimal RT method when attempting to enhance motor skills associated with speed, power and RFD (though both CT and ST improved muscular strength to comparable degrees). The performance enhancements associated with CT are reported to result from augmented muscle phosphorylation, calcium sensitivity and H-reflex activity following CT (Hodgson, Docherty, & Robbins, 2005; Robbins, 2005; Sale, 2002) in addition to increased CD34/CD45 immune system stem-cell secretions (Labib, 2013; Sidney, Branch, Dunphy, Dua, & Hopkinson, 2014) and preservation of type IIX muscle fibres (Bottinelli, Canepari. Pellegrino, & Reggiani, 1996; Harridge et al., 1996; Stasinaki et al., 2015). Another suggestion from the current literature relates to greater volume associated with CT interventions than those observed for other RT methods (Pagaduan et al., 2019). This may provide a larger training stimulus, and subsequently, produce greater muscular, neuromuscular and morphological adaptations (Wilson et al., 2013). Though it should be stated that if training volume is too high, greater degrees of neuromuscular fatigue maybe induced as a result of CT that may have a negative influence upon training adaptations when performed in conjunction with sport/technical practice (Carter, & Greenwood, 2014, Rajamohan et al., 2010, Wilson et al., 2013).

With regards to frequency, previous research reported that 2 CT sessions per week increased sprint performance to a similar degree as ≥ 3 weekly sessions (Alves, Rebelo, Abrantes, & Sampaio, 2010; Cavaco et al., 2014). In addition, lower weekly training frequencies are required to increase and/or maintain performance standards when certain muscles/body parts are regularly used during sport-specific training (Tan, 1999). Current literature concerning short- and long-term training adaptations associated with CT suggests interventions of ≥ 6 weeks are optimal for this training modality (Pagaduan et al., 2019). Therefore, though training responses and adaptations to CT are likely to be individualised, twice-weekly sessions for a minimum duration of 6-weeks (such as the present study) are effective at augmenting sprint performance, lower-body power and force-time characteristics (Freitas et al., 2017; Pagaduan et al., 2019).

Consequently, given the potential neural and morphological improvements achieved through CT, boxers are encouraged to integrate CT programmes with heavy (≥ 85% 1RM) and light (0-50% 1RM) RT loads to improve force-time characteristics at various points along the force-velocity curve (Haff, Whitley & Potteiger, 2001), in addition to increased type IIX muscle fibre proportion, fascicle pennation angles, and muscle fibre CSA. Such adaptations are likely to enhance physical performance-related characteristics associated with maximal punching (Chaabene et al., 2015; Chapter 5).

It should be stated that there were noteworthy baseline muscular strength differences recorded between groups prior to the 6-week training interventions (absolute 1RM = 5.1–7.3%, normalised 1RM = 5.5–5.8%). Additional analysis was conducted to control for these differences (see Appendix 7) and revealed significant differences between groups, further indicating the effectiveness of CT and ST interventions at augmenting physical performance-related qualities, in spite of baseline differences.

Though the efficacy of CT at augmenting physical performance-related variables has been reported (Argus et al., 2012; de Villarreal et al., 2013; Granacher et al., 2016; Pagaduan et al., 2019; Spineti et al., 2016), the optimal loading 'contrasting' (i.e. power) exercise loading parameter for boxers has yet to be identified. Indeed, high-load (≥ 85% 1RM) strength exercise and subsequent ballistic exercises of kinematic similarity performed with < 60% 1RM have been suggested to optimise maximum power output via increased motor unit recruitment, α-motor neuron excitability, and actin-myosin binding rates (Jones et al., 2013; Lim & Barley, 2016; Rassier & Macintosh, 2000). Meanwhile, other research advocates the use of ballistic body weight exercises (e.g. CMJ – Walker, Ahtiainen, & Häkkinen, 2010) and loaded throws (e.g. med-ball shot put) that simulate relevant sporting movements to increase punching performance (Lenetsky et al., 2013). A further option is the inclusion of maximal punches themselves as the 'contrasted' exercise (Turner et al., 2011), with the suggestion that pairing a multi-joint strength-based exercise with a maximal punch (e.g. rear-hand cross) may enhance movement-specific force-time characteristics (Sale, 2002), and develop the cognitive and physical application of the potentiated muscular effects to maximal punching (Turner et al., 2011). Therefore, future research should investigate the effects of CT protocols that employ different loading parameters for the ‘light/power’ exercises on the physical performance-related and biomechanical characteristics of maximal punches to establish the most effective loading parameter for amateur boxers.

Improvements in the ST group’s jump squat (8.5%) and bench throw (10.4%) are comparable to those reported recently (7% and 8%, respectively) by Loturco et al. (2018), while the CT group experienced noticeably larger increases of 16.7% and 15.8% from baseline. Such a difference corroborates previous findings that CT produces greater training adaptations than ST and/or power training performed in isolation (de Villarreal et al., 2011; 2013). Moreover, the significant muscular power (upper-, lower- and full-body) increases exhibited by both training groups, but particularly the CT group, corroborate the muscular power increases reported by Kobal et al. (2017), and underpin the importance of high-force exercises (≥ 85% 1RM) to the development of muscular power (Turner et al., 2011; Zatsiorsky & Kraemer, 2006). Indeed, muscular strength is reported to influence various force-time characteristics (e.g. rate of force development (RFD), stretch shortening cycle (SSC), external mechanical power) that can effectively translate to high-velocity athletic activities (Newton et al., 1997; Suchomel et al., 2016). This may explain, given the large associations observed in previous studies between shot put distance and biomechanical characteristics of maximal punching (Chapter 5; Obmiński et al., 2011), the current med-ball shot put distance increases exhibited by both ST (lead = 7.4%, rear = 6.4%) and CT groups (lead = 11.4%, rear = 6.2%), which were noticeably greater than those reported by Čepulėnas et al. (2011 - lead = 3.8%, rear = 3.5%).

It should be stated that the diverse nature of the workload between boxers may have impacted post-intervention results. Indeed, in accordance with findings in previous research, there is a possibility that the additional exercises completed by the

CT group meant they completed a greater total volume than the ST group, and subsequently, achieved greater neuromuscular system stimulation and adaptations (Pagaduan et al., 2019; Wilson et al., 2013). Though, conversely, greater training volumes associated with CT interventions may also induce higher levels of neural fatigue than in the other groups which are likely to negatively impact neuromuscular adaptations when combined with sport-specific technical/skill training (Carter & Greenwood, 2014; Pagaduan et al., 2019; Rajamohan et al., 2010; Walker, Ahtiainen, & Häkkinen, 2010). Therefore, it is difficult to accurately elucidate how the different 'workloads' of each RT intervention influenced the pre-to-post performance changes among ST and CT boxers despite total training intensity and volume across the 6-week interventions equated to the greatest degree between groups.

Additionally, boxers across all groups completed high-repetition callisthenic/bodyweight exercise exercises during boxing-specific skill/technical training sessions throughout the 6-week intervention period. Indeed, the C group completed bodyweight exercises within their boxing technical/skill training sessions as part of their warm up, sparring preparation and general 'conditioning' (e.g. various callisthenic exercises performed in a circuit fashion for a number of 'rounds'). From training diaries provided by all boxers over the 6-week period, C group completed a total 8233 ± 3952 repetitions of such exercises. Boxers in ST and CT groups also completed similar exercises as part of their boxing skill/technical sessions (ST = 5100 ± 2687 total repetitions, CT = 3900 ± 4480 total repetitions) in addition to their twice-weekly intervention sessions. This implies that although the C group completed a greater total volume of bodyweight/callisthenic exercises (that may have included plyometrics as part of boxer's circuit training or boxing 'conditioning' sessions), they did not evidence any worthwhile changes in maximal punch biomechanics or physical performance-related qualities.

In addition to bodyweight/callisthenic exercises, the total hours of boxing skill/technical training completed were 28.8 ± 3.4 (C), 27.2 ± 6.8 (ST), and 26.2 ± 5.8 (CT), respectively, over the 6-week intervention period, comprising ~2.5 (C), ~2.4 (ST), and ~2.3 (CT) skill sessions per week. Furthermore, boxers across all groups also completed conditioning-based training sessions throughout the intervention period (e.g. long distance running, sprint intervals) to enhance and/or maintain cardiovascular endurance and conditioning. According to training diaries, the total number of minutes completing such training over the 6-week period was 572 ± 288.1 (C), 280 ± 62.4 (ST), and 339.2 ± 208.1 (CT), respectively. Therefore, it is plausible that this additional exercise impacted on the post-intervention performance measures between boxers. Though both ST and CT groups made significant performance improvements from baseline measures in comparison to the C group, the additional training load accumulated by some boxers across the intervention period suggests it cannot be unequivocally stated the performance improvements were solely due to the RT interventions. However, despite this, both ST and CT groups completed less total callisthenic/bodyweight exercise repetitions and conditioning-based training than the C group across the 6-week intervention period, yet still increased their maximal punch biomechanics and physical performance to significantly greater magnitudes in comparison. This justifies the inclusion of RT interventions within amateur boxer's training programmes and reveals the stimulus achieved through ST and CT interventions is likely superior at increasing the biomechanical characteristics of punching and the physical abilities that underpin such movements (Chapter 5) in comparison to 'traditional pre-fight preparation strategies' of boxers (i.e. high-repetition bodyweight/callisthenic exercises and endurance running – Bourne et al., 2002; Del Vecchio, 2011; Price, 2006).

6.4.4. Body mass

The trivial increases in body mass observed by both intervention groups (0.6 kg) suggests a small increase in lean (muscle) mass, corroborating the trivial (~0.4-0.6 kg) body mass increases in Otto et al. (2012) and Støren et al. (2008) following 6-week and 8-week ballistic and ST interventions, respectively. This suggests that although the boxers in the current study had previous experience completing RT exercises, the stimulus of the ST and CT interventions still potentially increased body mass. These results suggest boxers who decrease their weight substantially prior to competition (i.e. to compete at the lightest weight category possible) should take into account the effects of ST or CT programmes on lean body mass to prevent the need for more radical weight loss strategies. Indeed, research has identified how acute body mass decreases hinder training adaptations prior to competition and diminish biomechanical and physical performance-related characteristics essential to successful combat sports performance, including fist velocity (Halperin et al., 2016b), punch force (Smith et al., 2001), and muscular strength and power (Roemmich & Sinning, 1996). Boxers should therefore endeavour to enhance their maximal strength and power levels (relative to their body mass) in an attempt to optimise biomechanical and physical performance-related characteristics of maximal punching, whilst remaining in the confines of their weight classification for competition. Taken together, it is recommended that coaches and boxers adapt/modify the training programmes presented herein according to boxer-specific characteristics, considering the magnitude and duration of required weight loss prior to contests, to facilitate and retain training adaptations whilst minimising lean body mass increases.

Though the C group also exhibited trivial body mass increases post-intervention, no performance increases were observed in comparison to the CT and ST groups. Indeed, the trivial-to-small changes across all strength assessments for the C group support previous notions that the typical stimulus achieved via boxing skills training alone (Fleck & Kearney, 1993), or in combination with unloaded high-repetition bodyweight/callisthenic exercises as is common practice among the boxing community (Bourne et al., 2002; Del Vecchio, 2011) is largely ineffective in enhancing the majority of biomechanical properties of punching and the physical abilities related to such movements.

6.4.5. Conclusion

In appraising the effects of six-week RT interventions on maximal punch kinetics and kinematics, the present study has identified that both ST and CT programmes were effective in enhancing the biomechanical and physical performance-related characteristics associated with six punch types essential to boxing. Moreover, as anticipated, larger improvements to these qualities were observed for CT, likely owing to improved upper-extremity function at high-velocities, larger lead leg musculotendinous stiffness and stability, and increased generation of rear leg kinetic energy resulting from neurological, morphological and architectural changes, in addition to the likely augmentation of lower-limb kinetic and kinematic varaiables (e.g. rear ankle, knee and hip joint extension angles, angular extension velocities and extensor moments – Chapter 3). Whilst these findings cultivate our understanding of the influence of different RT interventions on maximal punch biomechanics, future research should investigate the influence of adapted CT interventions and other RT methods (e.g. Olympic weightlifting) on maximal punch biomechanics, in addition to long-term (> 6 weeks) neurological, morphological and architectural changes in muscle from such interventions, with the overall aim of developing boxing- and punch-specific strength and conditioning strategies.

Chapter 7

Conclusions

7.1. Addressing the research questions

The aims of this series of studies were to investigate the kinetic and kinematic qualities (and MV) of maximal punches, quantify their associations with physical performance-related characteristics, and identify the extent to which RT might enhance such features in amateur boxers. Though there remains much to scrutinise in this context, it is anticipated that the findings reported in this thesis will impact on the training implemented (by coaches) and completed (by boxers), to augment performance. Such findings - sequentially illuminated in Figure 7.1 (below) - were borne out of four research questions:

i. **Which kinetic and kinematic measures are associated with maximal punching performance across conventional punch techniques?**

Chapter 3 identified that specific kinetics (peak lead and rear leg GRF, total lead and rear impulse) and kinematics (delivery time, peak fist velocity, peak joint angular velocities (shoulder and elbow), and the timings of these peak joint angular velocities, are associated with maximal punches performed by amateur boxers and vary according to punch type (straight, hook, or uppercut). For example, in terms of kinematics, straight punches were delivered the quickest, the lead hook exhibited the greatest peak fist velocity, and uppercuts exhibited the greatest joint angular velocities. The results in Chapter 3 present the kinetic and kinematic characteristics associated with each punch technique common to boxing competition and provide a more comprehensive analysis of the biomechanical variables associated with maximal punches than documented previously (e.g. Cabral et al., 2010; Cheraghi et al., 2014; Piorkowski et al., 2011; Whiting et al., 1988).

ii. **How does movement variability affect maximal punching performance and is it influenced by boxing experience?**

Chapter 4 revealed moderate-to-large within-subject, between-subject, and biological variability across punch types for the majority of the kinetic and kinematic variables examined during maximal punches. Furthermore, the non-significant inter- and intra-subject relationships between biomechanical variables and boxing experience indicated MV is not influenced by boxing experience and may be more dependent on a boxer's individual structural (anthropometric), functional (physiological and psychological) and task (pre-determined requirements of a competition or skill performance) constraints (McGarry et al., 2013). These findings contrast those in previous combat sport literature (Lenetsky et al., 2017), and suggest both experienced and novice boxers manipulate biomechanical variables via different coordination strategies in order to achieve a (relatively) consistent intensity and end-product.

iii. Are physical performance-related characteristics associated with maximal punching?

Following a comprehensive examination of the relationship(s) between physical performance-related measures and the biomechanics of maximal punches, physical 'ability' was often found to be related to the kinematics and kinetics of maximal effort punches (Chapter 5). More specifically, different physical traits were shown to influence specific punch types and/or biomechanical variables (e.g. sprint performance and peak rear leg GRF across all rear hand punches (cross, hook, and uppercut)). Furthermore, upper- and lower-body muscular strength was shown to relate to the peak fist velocities of most punch types, suggesting these physical traits influence punch kinematics in addition to previously established impact kinetics (Loturco et al., 2016).

iv. Can resistance training programmes enhance maximal punching performance?

Chapter 6 provided evidence to support the inclusion of ST and CT programmes in boxer's current training regimens, with both interventions enhancing all the physical performance-related and maximal punch biomechanical measures examined in Chapters 3 to 5. Though the findings corroborate earlier studies suggesting RT facilitates punch performance (Čepulėnas et al., 2011; Hlavačka, 2014; Kim et al., 2018), Chapter 6 reveals greater biomechanical and physical performance-related improvements were observed in the CT group, likely owing to the movement velocity affinity between the 'contrasted' power/ballistic exercises and maximal punching (i.e. high-velocity, low-to-minimal external load; Duthie et al., 2002). Importantly, Chapter 6 reflects the first study to establish positive changes in the biomechanical characteristics of maximal punching owing to RT, reinforcing its inclusion within a boxer's training. Understanding how RT influences maximal punch biomechanics (e.g. decreases delivery time, and thus affords an opponent less time to defend/evade) provides useful information to coaches and boxers in terms of potential training practices, and adds to previously identified punch impact force and power increases (Čepulėnas et al., 2011; Del Vecchio et al., 2017; 2019; Hlavačka, 2014; Kim et al., 2018) among boxers following RT.

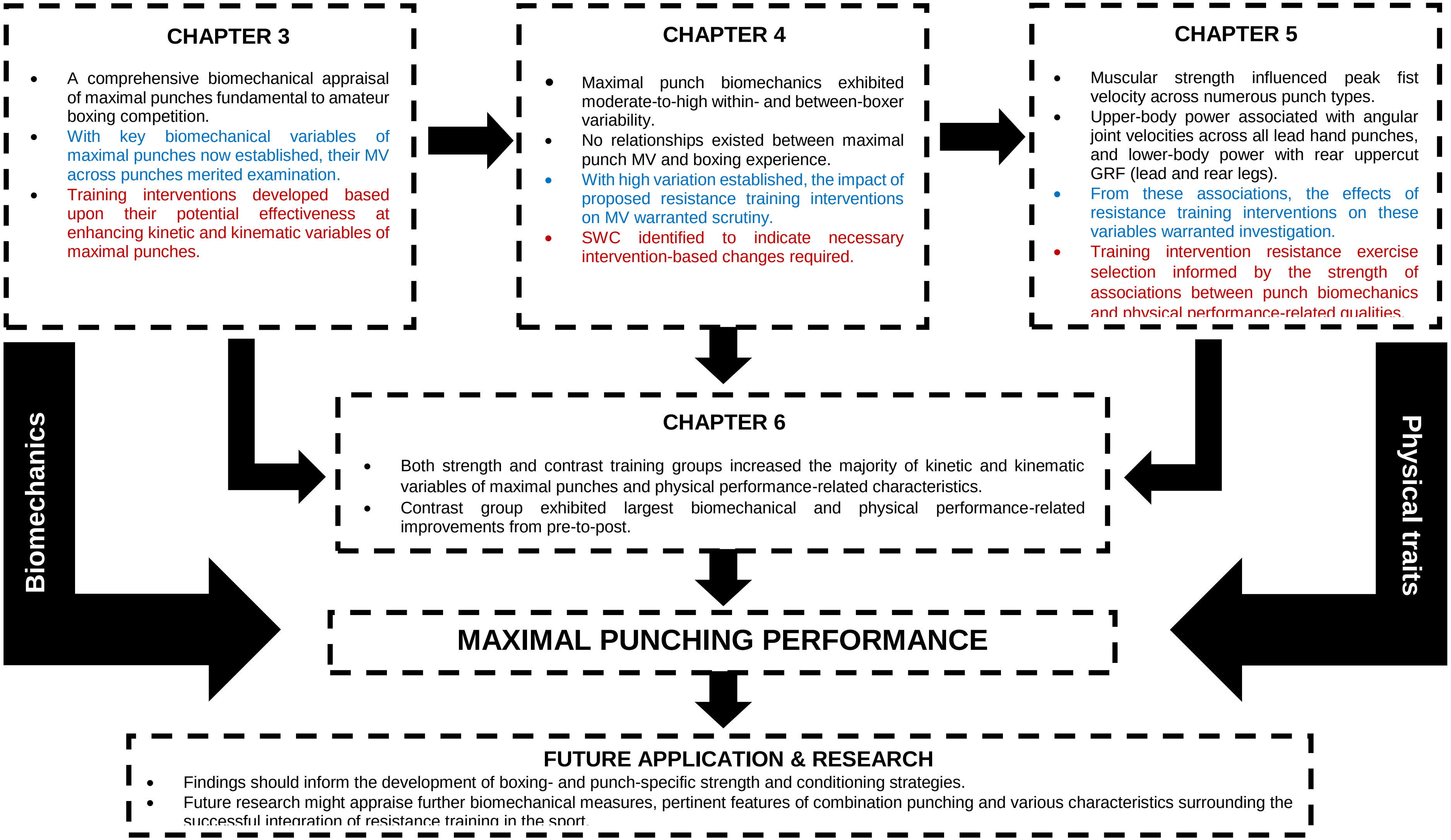

Figure 7.1. Schematic representation of the thesis (including each chapter's findings). Blue ink denotes how results informed subsequent chapter(s); red ink denotes how results informed the training interventions of Chapter 6.

7.2. Main findings and practical implications

7.2.1. Biomechanics and movement variability of maximal punches

In order to identify the biomechanical properties of maximal punches fundamental to boxing, a comprehensive analyses requires the combination of kinematic and kinetic data to quantify the motion and velocities of the upper-limbs, the forces produced by the lower-limbs, and how these forces are distributed between the lead and rear leg during different punch types (Lenetsky et al., 2013). Whilst previous research has investigated biomechanical characteristics of different punch types (Kimm & Thiel, 2015; Piorkowski et al., 2011; Walilko et al., 2010; Whiting et al., 1988), the majority only investigated a single punch type (e.g. rear-hand cross - Cheraghi et al., 2014) or kinetic/kinematic variable (e.g. fist velocity - Kimm & Thiel, 2015), and utilised a diverse range of measurement devices (e.g. life-size strike dummy - Piorkowski et al., 2011; foam-covered wooden target - Cheraghi et al., 2014). Thus, a comprehensive biomechanical analysis informed by key kinetic and kinematic variables (Chapter 3) was undertaken to quantify systematically the lower-body kinetics, upper-body kinematics, and movement variability (Chapter 4) of all punch types fundamental to boxing competition (straight, hooks and uppercuts).

Collectively, the findings of Chapter 3 established the key biomechanical variables influencing maximal punches, the kinetic and kinematic differences between punch types, and the movement variance from punch-to-punch. Moreover, the results identified potential symbiotic relationships between specific biomechanical variables (e.g. vertical GRF) and certain punch types (e.g. uppercuts), whilst interactions between lower-body kinetics and upper-body kinematics were also established. These discoveries appear to highlight the influence of lower-limb joint kinetics and kinematics in the transmission of energy and momentum to the fist via the generation of GRF in conjunction with sequential peaks in ankle, knee and hip joint extensions, extension velocities and extensor moments (kinetic chain) across punch types. Indeed, for straight punches (jab and rear-hand cross), lower-body joint segments (ankle, knee and hip) exhibit a progressive sequence of distal-to-proximal joint initiation, while the upper-body segments (shoulder and elbow) demonstrate inter-joint coordination that culminates in the projection of the fist towards the target. Meanwhile, for hook and uppercut punches, the lower-limb joint sequence is comparable to straight punches (i.e. successive ankle, knee and hip joint peak extension velocities and moments), though not for the upper-extremities whereby the elbow joint reaches peak angular velocity prior to the shoulder joint. Therefore, coaches and boxers ought to consider introducing technical (e.g. punch-specific drills and their integration within certain punch combinations) and resistance-based (e.g. landmine press to address shoulder and elbow angular velocities associated with straight punches) training sessions that address the biomechanical characteristics of punches.

Having identified the key biomechanical features of punching, the examination of technical consistency was warranted to identify potential MV, compensatory joint actions, and coordination strategies relevant to different punches. Understanding the MV of maximal punching and its magnitude across punch types could offer useful information pertaining to a boxer's technical progression following intervention-based changes. The appraisal of maximal punch MV in Chapter 4 revealed substantial inter- and intra-boxer variation for the majority of kinetic and kinematic variables and punch types, reinforcing that boxer-specific characteristics (e.g. arm segment dimensions, fighting/punching 'style', attentional focus and perception of own performance capabilities) contribute to high MV (Davids et al., 2006; Halperin et al., 2017).

Furthermore, the lack of associations between the variability of maximal punch biomechanics and boxing experience refutes the notion that novice boxers exhibit larger MV than experienced boxers. This is likely due to the dynamic nature of punching, whereby ballistic and accelerative phases of motion increase the probability of high MV as boxers compensate for superfluous movement in particular segments in attempts to ensure a relatively consistent end-product (Darling & Cooke, 1987; van den Tillaar & Ettema, 2006; Wagner et al., 2012). This suggests particular features of punching biomechanics are inherently erratic owing to an inter-dependent relationship between components of the kinetic chain and their degrees of freedom (mediolateral, anteroposterior, and transverse translations and rotations). In addition, the inter- and intra-subject variability between punch types and lack of relationship with years of boxing experience suggest MV is an intrinsic component of maximal punches.

In view of these findings, coaches are encouraged to tailor training practices to accommodate for variation in punching technique with the use of technical and tactical drills that facilitate effective maximal punches and punch combinations based upon a boxer's fighting 'style', and present boxing-specific analytical conditions (e.g. how to land a clean lead hook to the head of an opponent with a 'stylist' fighting style; Hickey, 2006; Thomson, 2015). Such practices may offer boxer-specific offensive strategies and purposeful solutions to the unpredictable nature of opponents and changeable demands of general competition, suggesting the quantification and regular monitoring of MV might be an effective tool for coaches and boxers. The monitoring of MV via a 'feedback loop' scheme (Figure 7.2) could foster the measurement of systematic changes and progressions in maximal punching performance. Providing systematic performance feedback to a boxer via this 'loop' could be a useful tool for monitoring maximal punches that could identify technical irregularities and behaviours, from which specific training practices and interventions could be developed (Preatoni et al., 2013). Consequently, the synthesis of the findings from Chapters 3 and 4 highlight the role of different biomechanical qualities to maximal punches and the magnitude of MV these qualities can exhibit from punch-to-punch and boxer-to-boxer. Taken together, these novel findings suggest the degrees of velocity (kinematics) and force (kinetics) associated with maximal punching, alongside the magnitude of MV observed, are likely consequential of the boxer-specific characteristics identified in previous research (Davids et al., 2006; Halperin et al., 2017), regardless of boxing experience. These findings should cultivate coaches and boxers understanding of the biomechanical and MV qualities of different punch types, which in turn, serve as a framework to direct and inform the development of punch-specific training practices.

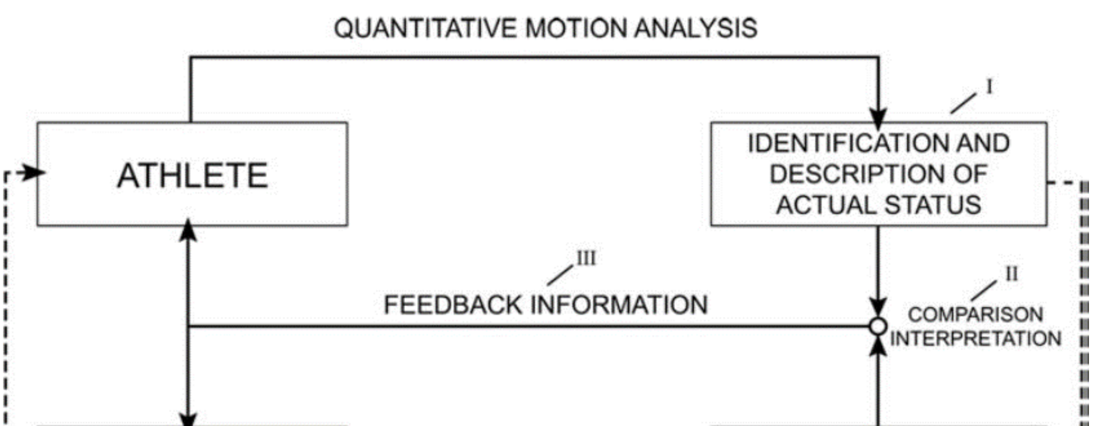

Figure 7.2. The athlete's monitoring scheme: (I) the robust description of motor characteristics; (II) the interpretation of biomechanical measures; (III) the translation of complex biomechanical analyses into readily comprehensible information for application on the field (taken from Preatoni et al., 2013, p.71).

7.2.2. Resistance training and its application to maximal punching

In order to develop RT programmes that enhance maximal punching performance and optimise boxer's contest preparation, the quantification of the physical qualities considered important to punching, and their association with biomechanical punch analyses, was necessary. Though previous research has investigated the associations between physical qualities and punch impact forces (Loturco et al., 2016; Pilewska et al., 2017), it only examined straight punch (jab and rear-hand cross) techniques. Quantifying the associations between maximal punch biomechanics and physical performance-related measures via a battery of physical assessments could provide a comprehensive representation of the influence that specific physical qualities have on maximal punching performance, and subsequently, encourage the development of training practices and punch-specific RT interventions.

To this purpose, Chapter 5 highlighted the association of muscular strength, power and speed qualities with the biomechanical characteristics underpinning maximal punches. More specifically, moderate-to-large relationships were found between measures of muscular strength, power, and speed and maximal straight punch kinetics and kinematics. Indeed, the findings suggest boxers might find it challenging to maximise the biomechanical qualities of maximal punches without possessing a degree of relative strength (Cormie et al., 2011), with this variable also influencing force-time characteristics (such as muscular power and speed; Suchomel et al., 2016). Notable associations were also documented for hook and uppercut punches, providing novel information concerning the importance of these physical qualities to all punch types. Moreover, with the findings in Chapter 5 showing the importance of muscular strength, power, and speed to maximal punching, it was necessary to establish if enhancing these physical traits via RT interventions could facilitate increases in maximal punch biomechanics. Consequently, a thorough appraisal of different RT protocols (with programme characteristics such as load and training modality informed by the associations established in Chapter 5) and their effects upon maximal punch biomechanics and physical performance-related qualities was undertaken (Chapter 6) to identify the optimal method/modality for improving these characteristics.

The investigation involving different RT programmes reported in Chapter 6 is the first study to reveal ST and CT interventions directly enhance maximal punch biomechanics and their underpinning physical performance-related qualities. Indeed, RT is effective at augmenting these qualities among amateur boxers. More specifically, both ST and CT protocols improved the majority of biomechanical and physical performance-related measures pre-to-post intervention, with the CT group exhibiting larger performance increases. This novel finding suggests that CT should be preferentially implemented within a boxer’s training programme as a means of enhancing maximal punching performance. Though the effects of CT on maximal punching biomechanics had not previously been examined, the larger performance increases among boxers following the CT programme compared to ST substantiated findings in other sports (de Villarreal et al., 2011; 2013; Hammami et al., 2017; Rahmi et al., 2005). Indeed, the elevated neuromuscular stimulation and musculoskeletal activation associated with CT protocols benefitted dynamic full-body movements performed at high-velocities (such as maximal punches) more so than ST alone (Seitz et al., 2014; Rassier et al., 2000; Tillin et al., 2009; Trimble & Harp, 1998). Consequently, the novel findings of Chapter 6 suggest CT was likely to have increased the upper-extremity function at high-velocities (Swanik et al., 2016) and enhanced the force generation capabilities of the lower-limbs (Davies et al., 2015); such changes plausibly combined to augment the kinetic and kinematic qualities of maximal punches among the boxers in this group. Thus, coaches and boxers are advised to re-examine the structure of their current training practices and consider the implementation of CT as part of their contest preparation strategies in order to improve boxing performance. This may be achieved via the development of a boxing-specific periodised training plan that is informed by the biomechanical and physical performance-related characteristics of maximal punching alongside the physiological requirements of competition (see Appendix 8).

The findings embedded within this thesis contribute novel empirical information to the understanding of maximal punch biomechanics, MV, and the physical qualities that influence them, in addition to the effects of different RT programmes on these characteristics of amateur boxing performance. The interaction between these characteristics and maximal punching performance provides valuable information to coaches and boxers pertaining to the physical performance-related variables influencing the technical intricacies of punching and potentially, boxing performance *per se*. As a whole, the contents of thesis enhance our understanding of maximal punching and the biomechanical and physical performance-related qualities that underpin it. Accordingly, such insight might inform pre-competition strategies based upon boxer's maximal punch biomechanics and physical performance-related measures, alongside their technical and tactical capabilities.

7.3. Limitations

7.3.1. External validity

7.3.1.1. Sample standard and size

Though all boxers were required to meet specific criteria to be eligible for each study (≥ 2 years boxing experience, and ≥ 2 official bouts), none were categorised as 'elite' (i.e. currently competing at international level). Experienced/elite boxers have been reported to exhibit superior punch forces (Joch et al., 1981; Leal & Spaniol, 2016; Smith, 2006; Smith et al., 2000), lower punch force variability (Lenetsky et al., 2017) and greater shoulder joint strength (Tasiopoulos et al., 2015; 2018) than less experienced/novice boxers. Likewise, higher peak fist accelerations and punch accuracy reported for experienced Kung Fu practitioners compared to novices (Neto et al., 2013). As a result of these biomechanical and physical performance-related differences between elite and sub-elite boxers and martial artists, it is acknowledged that the training stimulus required to achieve meaningful performance improvements may have to be larger for elite boxers than sub-elites. Though the training programmes presented in Chapter 6 might improve performance measures of elite boxers, it seems plausible the increases in such a cohort will not be of the same magnitude(s) as lesser trained boxers. Thus, future research is warranted to establish the biomechanical and physical performance-related measure changes resulting from RT programmes between elite and sub-elite standards of boxers to enhance the understanding of punch technique and training stimulus requirements according to ability.

With regard to sample size, each study (Chapters 3 to 6) in this thesis had appropriate sample sizes according to *α priori* (G*Power) calculations (see Appendix 1) and larger samples than comparable studies. However, previous authors have suggested that sample sizes > 40 are required for data findings to be accurately generalised across the relevant population (Atkinson & Nevill, 1998), particularly with respect to performance variability (Batterham & Atkinson, 2005). Indeed, systematic bias (e.g. general learning or fatigue effects on the tests) and random error (e.g. biological or mechanical variation) is suggested to influence intra-trial and test-retest measures positively (e.g. learning effect) or negatively (e.g. fatigue) (Atkinson & Nevill, 1998; Batterham & George, 2003), with an increased probability of high-performance variability with small sample sizes (Batterham & Atkinson, 2005). Therefore, given the necessity for large sample sizes to identify meaningful performance changes in the presence of systematic bias and variability, it is acknowledged the results presented herein may not accurately represent the maximal punch biomechanics, physical performance-related qualities and intervention-related performance changes of amateur boxers in general. Future research should therefore re-examine the performance variables appraised in Chapters 3-6 to detect maximal punch performance differences and changes using larger cohorts of boxers.

7.3.1.2. Laboratory environment

Previous research has established boxers and karatekas produce higher punch forces when standing at a self-selected distance from the target (Loturco et al. 2014; 2016; Neto et al., 2012). Though such research has not demonstrated if the variables recorded in this thesis are also impacted, a potential limitation of the current research relates to the fixed location of the punch target and force plates within the laboratory, which, for the taller boxers (≥ 1.8 m), might have resulted in fist contact prior to reaching full elbow extension during jab and rear-hand cross punches. Boxers were still able to execute punches at maximal intensity and demonstrate high fist velocities due to the utilisation of a punch target that moved upon impact (Atha et al., 1985; Nakano et al., 2014) and the biomechanical nature of the elbow whereby peak end-point fist velocity occurs prior to full arm extension (Piorkowski, 2009). Nonetheless, the peak fist and angular joint velocity values may have been affected by this laboratory setting. Future research therefore should examine the kinetics, kinematics, and MV of maximal punches executed from self-selected distances by amateur boxers. Identifying these differences should inform coaches and boxers as to the importance of judging and controlling distance in the execution of maximal punches (Bolander et al., 2009; Choi & Mark, 2004; Hristovski et al., 2006), and the movement variance between these conditions.

Furthermore, given the nature of a ‘live’ target (i.e. the opponent is reactive, potentially unpredictable, and poses an offensive threat) during competition, and that punches, even if maximal, are performed in an open environment, an experimental protocol that better replicates such conditions could provide comparatively valid data to better understand bout conditions. Indeed, previous research reported notably lower punch forces in competitive bouts compared to punches performed in laboratory settings (Pierce et al., 2006). In addition, punch assessments permitting combatants to step towards the target when striking (as is common in sparring and competition) have exhibited larger impact forces (~22%) and fist velocities (~10%) than stationary punches (Neto et al., 2012). Within this research, there was no additional footwork and/or punch preparation strategies prior to each punch trial nor were the trials executed in response to an external stimulus (e.g. light emitting diode (LED) located near to the punch target) and/or with the added threat of incoming punches (by a coach/boxer (Appendix 9) or appropriate boxing training device (e.g. Title 'Gladiator Stick', Title Boxing, Kansas City, United States (Appendix 10)). Despite potentially having less control over extraneous variables (e.g. additional footwork, defensive techniques etc.) using this protocol, such analyses could provide a more 'realistic' biomechanical assessment of punching that has a greater application to boxing competition.

7.3.1.3. Absence of footwear during punch trials

In attempts to create accurate foot segments and an overall lower-body marker model that would facilitate a precise assessment of lower-limb kinetics and kinematics in 3D spaces during maximal punches, boxers did not wear footwear of any kind (e.g. shoes, trainers, boxing boots etc.) during punch trials. Though no scientific research currently exists pertaining to the influence of footwear on maximal punch biomechanics, it is suggested that the barefoot condition of the punch trials in Chapters 3 and 6 may have affected the lower-limb kinetics and kinematics of boxers, and consequently, is a potential limitation. Indeed, the momentum generated via the kinetic chain is reliant upon the generation of energy from feet against the ground (Cabral et al., 2010; Cheraghi et al., 2014) and this may not have been optimised during barefoot punch trials in comparison to the same punches performed with footwear (e.g. boxing boots). Previous research has reported how footwear increases the degree of metatarsophalangeal (MP) joint flexion (dorsiflexion) and elongates the initial length of the plantar muscle during a 'push off' in badminton (Wei, Liu, & Fu, 2009). In addition, footwear has also shown to produce greater GRF variables and joint kinematics (ankle and knee) during drop jumps (Koyama & Yamauchi, 2018) and peak vertical GRF and rotational forces (Tz, Mz) in golf swings (Worsfold, Smith, & Dyson, 2009) suggesting it might have impacted the kinetic and kinematic values reported herein.

Future research should examine the kinetics, kinematics, and MV of maximal punches performed with amateur boxers wearing their preferred choice of footwear (e.g. boxing boots), and perhaps, compare results with the barefoot conditions of the current study. Identifying how boxing footwear affects maximal punches and the differences in comparison to barefoot punches could provide information to coaches and boxers concerning the effects of footwear on certain kinetic and/or kinematic variables during maximal punches, and potentially, how certain styles of footwear (i.e. a minimalist boxing boot vs a joint-supported boxing boot) affect maximal punches.

7.3.2. Omission of GRF moments

Though the current research quantified a selection of lower-body kinetic variables (peak GRF, peak joint moments and total impulse) across maximal punches, the analysis of GRF moments (Mz and Tz - vertical moments about the force platform(s) (Richards, 2008) may have afforded useful and novel information concerning the lower-limb rotational forces of maximal punches. Mz represents the rotational moment about the vertical axis of the force platform(s) resulting from shear forces between the foot and ground (Worsfold, 2006), while Tz signifies the free moment about the subject's centre of pressure (Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2013). Whilst previous research has reported the GRF moments of golf swings (Worsfold, Smith, & Dyson, 2008), softball hitting (Iino, Fukushima, & Kojima, 2014) and tennis strokes (Akutagawa & Kojima, 2005), respectively, free moment analysis is limited within sports performance research (Fujii, Yamashita, Kimura, Isaka, & Kouzaki, 2015) analysis. Indeed, no research currently exists that has quantified the free moments of punches or other striking techniques (e.g. kicks) observed in combat sports. Consequently, the current research did not examine GRF moments due the difficulty in making meaningful inferences given the lack of normative data and comparative values relevant to punching performance in the literature. However, it is acknowledged that the analysis of these variables may be useful in determining the rotary forces and mechanics of maximal punches. Indeed, quantifying the Tz and Mz of the lead and rear legs (alongside GRF, joint moments and impulse) could offer more detailed information concerning the role of each leg in absorbing force and offering stability during maximal punches (lead leg), in addition to the rotational forces and traction properties (rear leg).

7.3.3. Overall training load during resistance training interventions

The findings presented in Chapter 6 highlight the effectiveness of twice-weekly ST and CT sessions on maximal punch biomechanics and physical performance-related variables in comparison to boxing practice only (control group). However, though the boxers were advised to reduce the volume and/or frequency of their boxing-specific and cardiovascular-based training sessions to accommodate for the RT interventions, it is possible that overall training load varied between boxers across each group. Indeed, the lack of detailed descriptions concerning boxer's entire training load (comprising concurrent aerobic, anaerobic, RT, and boxing-specific training sessions) across the 6-week period means that it cannot be stated unequivocally that the RT interventions were solely responsible for the maximal punch and physical performance-related improvements documented by ST and CT groups. Though training diaries completed over the six-week intervention period suggest differences between boxers and groups existed despite the intervention sessions being completed as suggested, the variation in training load means that some boxers may have diminished their potential performance adaptations resulting from additional cardiovascular- and boxing-specific conditioning training alongside the intervention sessions in attempt to maintain their endurance and fighting weight (Bourne et al., 2002; Del Vecchio, 2011). Indeed, combining strength and endurance-training within the same training cycle (known as 'concurrent training') is reported to be sub-optimal for muscle strength and power development (Wilson et al., 2012), resulting from the 'interference phenomenon' (Hickson, 1980), whereby strength and power training adaptations are blunted when two disparate forms of muscular contraction (i.e. strength and endurance) are trained simultaneously (Doma et al., 2019; Enright, Morton, Iga, & Drust, 2017). Therefore, it is unknown if such improvements were maximised given the additional cardiovascular and conditioning-based sessions performed throughout the intervention period. Nontheless, in spite of this, both intervention groups made significant performance improvements from baseline measures in comparison to the control group which highlight the potential benefits of structured RT interventions to amateur boxers.

A method that coaches and boxers could introduce as a means of monitoring overall training-load during training interventions is the calculation of 'total weekly training-load' for each training session (and competitive bout(s) if needed) via the rating of perceived exertion training-load (RPE-TL) method (Impellizzeri, Rampinini, Coutts, Sassi & Marcora, 2004). This involves performers rating the intensity of a training session within 30 minutes of its conclusion using the Borg 10-point RPE scale (Dias, Simão, Saavedra, Buzzachera, & Fleck, 2018; Haddad, Stylianides, Djaoui, Dellal, & Chamari, 2017) and multiplying the RPE value by the duration of the training session (in minutes) to offer an indication of the total training-load (Enright, 2014). From this, a valid method of quantifying weekly training-load can be achieved by summing the RPE loads of RT, endurance training and sport-specific technical/skill sessions (Impellizzeri et al., 2004). Furthermore, calculating the ''total resistance-training-load' of RT sessions may assist in monitoring programme variables comprising RT interventions (e.g. repetitions, sets, training intensity (% 1RM lifted)) by multiplying repetitions, sets and training intensity to obtain one arbitrary unit for comparison (AU) (Enright, 2014; Haff, 2010; Heaselgrave, Blacker, Smeuninx, McKendry, & Breen, 2019; Peterson, Pistilli, Haff, Hoffman, & Gordon, 2011). Future research could also examine the long-term effect and relationship of weekly training-load on maximal punching and physical performance in attempts to quantify the optimal training load to facilitate training adaptations whilst minimising peripheral and central fatigue (Márquez et al., 2017; Zając, Chalimoniuk, Maszczyk, Gołaś, & Lngfort,

2015) and accommodating for the physiological and mechanical demands of boxing-specific training modalities (Finlay, Grieg, McCarthy, & Page, in press).

7.3.4. Baseline discrepancies in muscular strength measures

Analyses in Chapter 6 evidenced significant pre-to-post intervention improvements in maximal punch biomechanics and physical performance-related qualities having controlled for baseline differences in muscular strength between groups following CT and ST programmes (see Appendix 7). However, in spite of this additional analysis, it should be stated that these baseline strength differences (particularly for the back squat) could have influenced the magnitude of performance improvements and adaptations following the RT interventions, and as such, should be stated as a potential limitation of this particular intervention.

Previous research has reported how muscular strength influences numerous force-time characteristics (such as RFD, SSC, neuromuscular power, external mechanical power and limb acceleration), that subsequently influence athletic activities involving high-velocity motion and movements (Newton et al., 1997; Suchomel et al., 2016; 2018), based on the linear relationship between force and power production (Cormie et al., 2011a; 2011b). Therefore, it is plausible to suggest that the CT group were perhaps more likely to achieve greater training adaptations, and consequently, performance improvements in maximal punching and physical performance-related qualities given their greater baseline back squat 1RM values compared to C and ST groups. This is supported by findings in previous research whereby lower-body muscular strength has correlated with the peak fist velocities, upper-limb joint angular velocities (Chapter 5), accelerations (Loturco et al., 2014) and impact forces (Loturco et al., 2016) of maximal punches, in addition to lower-body RFD (Andersen & Aagaard, 2006; Kraska et al., 2009; Thomas et al., 2015), external mechanical power (Cormie et al., 2010; Drid et al., 2015; Gorostiaga et al., 2005), jumping (Cormie et al., 2010; Kraska et al., 2015; Sheppard et al., 2008), sprinting (Barr, Sheppard, Agar-Newman, & Newton, 2014; McBride et al., 2009; Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004) and agility (change of direction) (Spiteri et al., 2013; Spiteri, Newton, & Nimphius, 2015; Young, Miller, & Talpey, 2015).

Furthermore, the 'contrasting' exercises (i.e. power exercises) in the CT intervention were completed with loads irrespective of body mass and/or absolute muscular strength (e.g. bodyweight for CMJ, 3kg for med-ball slams). Whilst the optimal load for 'contrasting' exercise loading parameters for boxers has yet to be identified, findings in recent research (Loturco et al., 2018; 2019), suggest that individualising power training intensities according to a boxer's physical capabilities may have enhanced acute muscular power responses to CT, including peak power and force-time characteristics, to a greater degree than the methods utilised in Chapter 6. Indeed, the use of Optimum Power Loads (OPL - load capable of maximising power output) has increased peak power output in the jump squat (+7%) and bench throw (+8%) among elite amateur boxers after a 7-week intervention (Loturco et al., 2018), in addition to punch impact forces after a one-week intervention implementing the same protocol (~8%) (Loturco et al., 2019). Though the CT group exhibited larger jump squat (16.7%) and bench throw (15.8%) performance increases, the standard of boxers in previous research (Olympic boxers - Loturco et al., 2018; 2019) compared to those in Chapter 6 signify that the comparison of results should be made with caution given that experienced/elite boxers have exhibited greater punch forces (Joch et al., 1981; Leal & Spaniol, 2016; Smith, 2006; Smith et al., 2000) and greater strength

(Tasiopoulos et al., 2015; 2018) than sub-elite boxers. Therefore, the training stimulus required to achieve meaningful performance improvements will likely have to be greater for elite boxers than sub-elites, and so, the power/'contrasting' exercise training load may need to be tailored specifically to individual boxers as their standard increases.

As a result of the baseline strength differences and lack of boxer-specific power training loads, future research should investigate the effects of CT interventions on maximal punch biomechanics and physical performance-related qualities that implement individualised training intensities/loads for the 'contrasting' exercises over various intervention durations (e.g. 8–16-weeks) with boxers of comparable strength levels. This may help to elucidate the acute and chronic responses/adaptations to such training programmes that could assist in determining the most effective power loading parameters and mesocycle lengths for amateur boxers.

7.3.5. Replacement of training sessions

All boxers that undertook the ST and CT interventions (Chapter 6) performed all 12 of the assigned RT sessions across the 6-week intervention period (100% adherence rate). Prior to the interventions, boxers were instructed to remove one regular boxing skill/technical session and one cardiovascular/endurance training session each week in order to accommodate for the twice-weekly intervention sessions. However, given the diverse nature of each boxer's weekly training regimen and workload prior to and during the RT interventions (e.g. intensity, duration and number of weekly boxing skill/technical, endurance-based, and circuit training sessions), their dissimilar weekly schedules, and ambiguity of the individual training diaries provided, it is unknown if all boxers adhered to this instruction. Therefore, it is possible that boxers self-selected the sessions to be removed each week which could have affected the acute molecular responses and overall adaptations to the RT interventions (Coffey & Hawley, 2006). Further research is required to elucidate whether the addition and replacement of specific endurance and boxing skill sessions, and the temporal structure of strength and endurance-based sessions, impacts boxer's acute and chronic muscle performance and recovery in addition to maximal punch biomechanics and physical performance-related qualities. Indeed, the application of a controlled and monitored training environment may offer useful evidence that can be used to inform and develop boxer's training programmes and strategies to optimise performance and recovery.

7.3.6. Interval between the assessment of maximal punch biomechanics and physical-performance related qualities

It is acknowledged the ≤ 30 day interval between biomechanical and physical assessments in Chapter 5 may have influenced the reported relationships between maximal punch variables and physical performance tests. Such an interval between assessments may have afforded boxers the opportunity to increase (or decrease) their physical-performance qualities (or even enhanced their punching technique) having already completed the maximal punch assessments. Though the majority of boxers completed both assessments within ~96 hours of each other (and all assessments by all boxers completed in the morning (~10:00 hrs)), some boxers could only be tested at specific times (i.e. anywhere up to 30 days) after the initial testing day due to the diverse and complex schedules of the sample. Ideally, all boxers would have completed both assessments within 48-72 hours of each other as is recommended in the literature (Haff et al., 2016; Tanner et al., 2013), which would have prevented opportunities for boxers to augment their punching or physical performance qualities considerably between assessments. Therefore, in order to validate the relationships presented in Chapter 5, future research should perform maximal punch and physical performance tests in a controlled environment with a standardised protocol to examine if associations between such variables differ in comparison to those presented in the current thesis.

7.3.7. Training session sequence, organisation and nutrient availability

Boxers are required to train a diverse range of physical and physiological qualities amateur that must be accommodate for within their training (e.g. muscular strength, power, speed, aerobic endurance and anaerobic capacity - El Ashker et al., 2018; Slimani et al., 2017; Thomson et al., 2017b), in addition to sport-specific training (i.e. technical practice, sparring). Consequently, boxers often train several times each day, performing sessions that emphasise varying mechanical demands (e.g. RT and endurance training (ET)), with the intent of augmenting multiple physical and physiological qualities (Finlay et al., in press). This was the case with the boxers in Chapter 6, whereby additional sessions were completed, and in some cases, on the same day(s) despite them being asked to refrain from performing additional training sessions (RT- or endurance-based) outside of their programmed RT and boxing training sessions for the duration of testing and 6-week intervention period. Large training loads and the demands (intensities and volumes) of different training sessions can bring about considerable metabolic stress on the body (Goto, Ishii, Kizuka, &

Takamatsu, 2005; Goto, Ishii, Kurokawa, & Takamatsu, 2007) and influence the magnitude of responses and adaptations to each physical/physiological quality trained (Doma et al., 2017; 2019), including acute and chronic molecular (Coffey, Pilegaard, Garnham, O'Brien, & Hawley, 2009) and metabolic (Goto et al., 2005) responses. Therefore, factors that were not strictly monitored in Chapter 6, such as sequence of training sessions, the time of day sessions were performed, and nutrient availability around training sessions may have influenced the post-intervention training responses and adaptations of boxers, and as such, should be considered a limitation.

The sequence of training sessions (e.g. RT before ET or ET before RT) and timing of sessions (i.e. morning or evening) are aspects of programme design that influence important biological and molecular functions and mechanisms responsible for training adaptations, such as intramuscular signalling (Atkinson et al., 2010), mTOR (Cunningham et al., 2007), peroxisome proliferator-activated receptor gamma coactivator-1 (PGC-1) (Baar, 2014) and protein synthesis (Carrithers et al., 2007). Both RT and ET trigger unique biological and biochemical mechanisms that generate differing intramuscular processes (Atherton et al., 2005; Fyfe et al., 2014; Robineau et al., 2016), with adenosine monophosphate-activated kinase-peroxisome proliferator activated receptor gamma coactivator-1 (AMPK-PGC-1) being up-regulated following ET, and Akt/protein kinase B-mammalian target of rapamycin-p70 S6 kinase (Akt-mTOR-S6K) pathways up-regulated following RT, respectively (Enright, 2015). The differing processes between RT and ET mean that the initiation of the mTOR pathway can be suppressed if sessions are performed in close proximity (< 6 hours) (Baar, 2014; Coffey et al., 2009; Robineau et al., 2016), and subsequently, can attenuate muscle protein synthesis (Breen et al., 2011) and the adaptive responses to both RT and ET (Cunningham et al., 2007; Hawley, 2009). More specifically, performing ET immediately after RT in the morning has been reported to impair muscular strength, power and morphology improvements (Enright, 2015 Indeed, many of the intramuscular signalling mechanisms activated by endurance exercise inhibit mTOR and protein synthesis attenuating adaptations to RT when training both qualities concurrently (Baar, 2014; Chinsomboon et al., 2009; Wu et al., 2011). This could have influenced the adaptations achieved by the boxers in Chapter 6 who may have performed ET or boxing training sessions in close proximity to their intervention RT sessions.

Previous research has reported how anything less than 6 hours between RT and ET sessions blunts molecular signals (Coffey et al., 2009) due to residual muscular fatigue and/or diminished intramuscular signalling and anabolic responses (Baar, 2014; Fyfe et al., 2014). Although performing RT and ET on the same day can maintain and/or improve performance (Lundberg et al., 2012; Murlasits, Kneffel, & Thalib, 2018; Petré, Löfving, & Psilander, 2018; Valéria et al., 2018; Wang et al., 2011), it is recommended that RT and ET be performed on alternate days to afford adequate recovery between modes of exercise that regulates residual fatigue, and therefore, fosters high training intensities and optimised strength, power and endurance adaptations (Eddens, van Someren, & Howatson, 2018; Shamim et al., 2018). Consequently, given that training multiple physical qualities simultaneously can compromise potential adaptations compared to independent training (Doma et al., 2017; 2019; Wilson et al., 2012), and sessions performed in close proximity can attenuate adaptive processes (Coffey, et al. 2009; Goto et al., 2005; Goto et al., 2007; Robineau et al., 2016), the boxers in Chapter 6 may not have maximised the potential benefit of the ST and CT interventions. Future research should investigate the effects of strictly regimented RT interventions performed in conjunction with ET and boxing-specific sessions on maximal punches and physical performance-related qualities.

Nutritional strategies can also affect intramuscular and biological processes associated with training-induced muscle adaptations (Tipton, 2008; Tipton & Wolfe, 2004). Indeed, the consumption of carbohydrate and protein sources before, during, and after training session (both RT and ET) can positively influence a range of biochemical and molecular responses associated with chronic adaptation and acute muscle performance (Hawley, Hargreaves, & Ziegrath, 2006), including mTOR, PGC-1 and protein synthesis (Barr, 2014; Carrithers et al., 2007; Churchley et al., 2007; Creer et al., 2005; Cunningham et al., 2007; Loenneke, Loprinzi, Murphy, & Phillips, 2016; Shamim et al., 2018). Previous research has reported how carbohydrate supplementation around both ET and RT sessions can regulate the rate of muscle glycogen depletion and facilitates the rate of glycogen resynthesis after exercise (Breen et al., 2011; Burke, Hawley, Wong, & Jeukendrup, 2011; Shamim et al., 2018; Xu, Ji, & Yan, 2012). Moreover, the addition of protein sources before, during, and after training sessions can maximise the anabolic response to RT by triggering mTOR, increasing muscle protein synthesis, enhanced muscle glycogen sparing, prevention of low blood glucose concentration, and increasing glucose availability via hormonal responses to insulin (Breen et al., 2011; Jeukendrup et al., 2011; Shamim et al., 2018). These responses to protein and carbohydrate ingestion around training sessions creates an anabolic environment that leads to superior intramuscular signalling (Enright, 2015), which is particularly important for athletes completing multiple daily training sessions (Baar, 2014; Breen et al., 2011). Therefore, as the nutritional strategies of boxers in Chapter 6 were not monitored, it is possible the biological and molecular functions responsible for training adaptations were hindered due to inadequate and/or insufficient nutritional strategies. Indeed, muscle glycogen can be depleted by as much as 40% following a single bout of running (Tesch et al., 1998), which can blunt biochemical and cellular pathways associated with muscle strength and hypertrophy (e.g. mTOR, muscle protein synthesis - Creer et al., 2005, Churchley et al., 2007; Shamim et al., 2018) in addition to negatively affecting performance in subsequent high volume, high-intensity and high skill training (Rico-Sanz, Zehnder, Buchli, Dambach, & Boutellier, 1999; Tesch, Ploutz-Snyder, Yström, Castro, & Dudley, 1998). Thus, when multiple bouts of training are performed on a daily basis, careful consideration and provision of protein and carbohydrates (i.e. timing, quality and quantity) is required to optimise biochemical and molecular responses to training and improve subsequent performance(s) and recovery (Baar, 2014; Enright, 2015; Kessinger, 2018; Phillips & Van Loon, 2011; Zehnder, Rico-Sanz, Kühne, & Boutellier, 2001).

Consequently, future research should therefore investigate how controlled and closely monitored nutritional strategies/interventions (particularly around training sessions) influence such qualities alongside muscle performance and recovery among amateur boxers. For example, this can be accomplished by having boxers ingest combined whey protein or Essential Amino Acids (EAAs) and fast-digesting carbohydrates before and after RT and ET sessions given the effectiveness of these nutritional supplements in enhancing training performance and acute and chronic adaptations (via biochemical and molecular responses) in previous research (Drummond, Dreyer, Fry, Glynn, & Rasmussen 2009, Farnfield, Breen, Carey, Garnham, & Cameron-Smith, 2012; Loenneke et al., 2016; Rasmussen et al., 2000; Shamim et al., 2018; Vieillevoye, Poortmans, Duchateau, & Carpentier, 2010).

7.4. Future directions

7.4.1. Integration of maximal punch kinetics, kinematics, and punch impact biomechanics

Though an extensive analysis of punch biomechanics has been achieved, further variables (such as punch impact force) could be examined to provide a more comprehensive biomechanical analysis of punching. Indeed, punch impact force has been identified as a key characteristic of maximal punching (Lenetsky et al., 2013; Loturco et al., 2016; Turner et al., 2011), underpinning a boxer's competitive level (Pierce et al., 2006; Smith, 2006), and considered fundamental for successful boxing performance (Chaabene et al., 2015). Integrating impact force values with 3D kinetics and kinematics (Chapter 3) (and potentially, joint powers, torque and GRF moments – Buśko, 2016; Janiak, Gajewski, & Trzaskoma, 1998; Karpilowski et al., 2011; Koryac, 1991; Pedzich et al., 2012; Tasiopoulos et al., 2015; 2018) would therefore provide a greater understanding of the biomechanics of different punch types and the relationship between impact and joint kinetics and lower-body kinetics (e.g. peak rear leg GRF), and upper-body kinematics (e.g. peak fist velocity). This would facilitate a better biomechanical understanding of the different punches that, if used according to the guidance of Preatoni et al. (2013) (Figure 7.2), could inform boxer's training practices.

7.4.2. Electromyographic analyses of maximal punches

The findings of Chapters 3 and Chapter 5 provide detailed information concerning the biomechanics of physical performance-related qualities underpinning maximal punches. However, it is acknowledged further investigation is required to obtain a more complete understanding of the role of specific musculature to different punch techniques. A conventional means of achieving this goal, and in particular, recognising the muscular activation patterns underpinning maximal punches, could be the use of EMG analysis. Previous research has investigated the muscular activity across straight punches (Dyson et al., 2007; Lockwood, & Tant, 1997; McGill et al., 2010; Valentino et al., 1990; Zhang & Kang, 2011), and hook punches (Lenetsky et al., in press), identifying the role of the upper-body, lower-body, and trunk musculature to these punches. Therefore, relating EMG data to the maximal punch biomechanics (Chapter 3) and MV (Chapter 4) could assist in identifying the influence specific musculature exerts on facilitating maximal punch performance and the development of punch-specific technical- and strength and conditioning-based strategies.

7.4.3. Biomechanics of combination punches

Though single maximal punches are important to boxing performance (Smith, 2006; Smith & Draper, 2007), combination punches are also imperative, with ≥ 2 (Davis et al., 2013; El Ashker, 2011) and ≥ 3 punch combinations (Slimani et al., 2017) indicative of successful boxing outcome, irrespective of ability level (novice or elite). Only two studies of note have compared the biomechanical features of combination and single maximal punches (Piorkowski et al., 2011; Whiting et al., 1988), with single maximal punches exhibiting greater peak fist velocities than combination punches, but longer delivery times (due to longer counter-movements at initiation). These studies provide useful information pertaining to kinematic differences in single and combination punches, but further research is required to adequately establish the kinetic and kinematic differences between various punch combinations (e.g. a jab followed by a rear-hand cross versus a lead hook followed by a rear uppercut) and the different number of punches within combinations (e.g. two, three, and four punch combinations). Quantifying the kinetic and kinematic qualities of different punch combinations could assist in informing boxer's training practice and contest preparation strategies by characterising specific biomechanical attributes between combination modalities (e.g. largest peak fist velocities, lowest delivery times etc.), potentially providing coaches and boxers with an understanding of which punch combinations have the greatest probability of yielding successful boxing outcomes.

7.4.4. Effects of different resistance training methods on punching performance

Notwithstanding the findings reported in Chapter 6, the effects of other RT methods (e.g. OL, BT, and PT) on the punch biomechanics and performance-related variables were not investigated. Furthermore, Chapter 6 demonstrated CT was more effective than ST at increasing maximal punch biomechanics and the physical qualities influencing them. Despite these performance changes, the optimal loading parameter(s) for the power/'contrasted' exercises fundamental to CT are unclear, particularly with regards to punch performance. Previous recommendations allude to ballistic exercises performed with 30-60% 1RM (Jones et al., 2013) and plyometrics with added loads (de Villarreal et al., 2013), while boxing-specific recommendations include bodyweight ballistic/plyometric exercises, various med-ball throws (Lenetsky et al., 2013), and maximal punches themselves (Turner et al., 2011) to be the optimal loading modalities. Consequently, future research ought to expand upon the results presented in Chapter 6 by analysing the impact of different RT interventions and CT protocols on maximal punch biomechanics and physical performance-related measures to ascertain the efficacy of each modality.

7.4.5. Bilateral versus unilateral resistance exercises

The training interventions documented in Chapter 6, in addition to the majority of previous research examining the effects of RT programmes upon punching performance, have utilised predominantly bilateral exercises (e.g. back squat) in their programme design (Čepulėnas et al., 2011; Del Vecchio et al., 2019; Kim et al., 2018; Loturco et al., 2018). Though the efficacy of bilateral exercises at augmenting maximal punch biomechanics has been established across these studies, previous literature has suggested unilateral exercises (e.g. rear-foot elevated split squat) may have a superior transfer to sports performance as a result of the 'bilateral deficit', in addition to the correction of muscular imbalances (Behm et al., 2005; Costa et al., 2015). Indeed, given the characteristic 'split stance' (i.e. left foot leading (orthodox) or right foot leading (southpaw)) adopted by boxers during training and competition (Hickey, 2006), it seems that unilateral exercises, particularly for the lower-body, may have a positive transfer to boxing performance. Moreover, unilateral muscular strength disparities between upper-limbs (Tasiopoulos et al., 2015; 2018) and lower-limbs (Mavi Var, 2019) have been identified among boxers, along with significant peak force imbalances between dominant and non-dominant limbs (Dos'Santos, Thomas, Jones, & Comfort, 2016), highlighting the potential benefits of unilateral exercise for correcting muscular imbalances typical of the sport. Additionally, the associations between GRF and certain physical qualities (lead leg GRF = muscular strength, rear leg GRF = speed) reported in Chapter 5 suggest the application of different RT exercises for particular limbs (i.e. lead leg = high-force; rear leg = high-velocity) might be warranted to optimise maximal punching performance. Therefore, as the effects of unilateral training on maximal punch biomechanics and their comparisons with bilateral training have yet to be appraised, future research should analyse intervention-based performance changes resulting from these training methods (see Appendix 11; for example, CT-based bilateral and unilateral training programmes). Such insight could establish the optimal training modality for enhancing punching performance that in turn cultivates the development of comprehensive boxing- and punch-specific strength and conditioning strategies.

7.4.6. Concurrent training

In addition to muscular strength, power, and speed, competitive boxers also require high levels of cardiorespiratory fitness, including aerobic and anaerobic capacity, anaerobic power and lactate tolerance (Chaabene et al., 2015; El Ashker et al., 2018; Hanon, Savarino, & Thomas, 2015; Slimani et al., 2017; Thomson et al., 2017b). In order to maximise competitive performance, a boxer's training must accommodate a diverse range of physical and physiological qualities, alongside technical skills, sport-specific conditioning (i.e. sparring) and pre-fight strategies/tactics. However, completing a range of diverse training interventions within the same training cycle (known as concurrent training; Enright et al., 2017) to enhance each attribute can potentially 'blunt'/compromise training adaptations compared to independent training due to the 'interference' phenomena (Wilson et al., 2012) and 'resistance training-induced sub-optimisation on endurance performance' (RT-SEP) (Doma et al., 2017; 2019) effect. Previous research has identified performing resistance and endurance-based training in close proximity (0 to 6 hours between sessions) is sub-optimal for developing neuromuscular and aerobic qualities (Robineau et al., 2016). Indeed, endurance training performed pre- (residual muscular fatigue) and post-RT (attenuated anabolic response) is reported to impair the quality of subsequent training sessions (Baar, 2014; Fyfe et al., 2014) resulting from RT-SEP (Doma et al., 2019). However, other studies have reported contradictory findings, with endurance training bearing no influence on strength increases when performed post-RT (Petré et al., 2018), and have even reported to augment lower body strength (with unaffected aerobic capacity adaptations) when performed pre-RT (Murlasits et al., 2018; Valéria et al., 2018).

In relation to boxing, concurrent training recommendations for professional boxing exist within the literature (Ruddock et al., 2016), but the performance changes of amateur boxers engaged in concurrent training have not been investigated. Previous research has reported punch biomechanics and physical performance-related improvements following RT (Čepulėnas et al., 2011; Del Vecchio et al., 2017; 2019; Hlavačka, 2014; Kim et al., 2018; Markovic et al., 2016) and boxing-specific punching drills (Kamandulis et al., 2018) among amateur boxers when performed in isolation, but not concurrently. The dearth of knowledge in this area means coaches and boxers are unlikely to have a comprehensive understanding of how to optimally integrate resistance- and endurance-based training sessions alongside each other (in addition to technical/skill practice). Identifying effective organisational approaches to a boxer's training practice that limit the 'interference' and RT-SEP phenomena through the manipulation of variables such as inter-session recovery periods, endurance training modality (i.e. long slow distance (LSD) versus HIIT (high intensity interval training), volume and/or intensity, and training session sequence (i.e. strength followed by endurance), may lead to greater training adaptations, and subsequently, improved performance (Doma et al., 2019). Therefore, scrutinising the changes to amateur boxing performance-related measures (biomechanical, physical and physiological) following concurrent training is warranted and may have significant implications for the development and implementation of boxer's strength and conditioning programmes.

7.4.7. Boxing-specific periodisation strategies

Finally, it is recommended future research also investigates periodisation strategy for amateur boxing, given the range of physical performance-related qualities required for successful performance and the necessity for such qualities to be programmed adequately in order to bring about performance improvements. For example, previous researchers have documented significant punch performance changes following specific RT interventions (Čepulėnas et al., 2011; Del Vecchio et al., 2017; 2019; Hlavačka, 2014; Kim et al., 2018; Markovic et al, 2016), whilst others have not (Bružas et al., 2008), suggesting the programme characteristics, including for example training load, intensity and exercise selection, are potential moderating variables worthy of attention (Hlavačka et al., 2017; 2018; Ke-tien, 2012; Marques et al., 2017). Furthermore, the physiological and mechanical demands of boxing-specific training modalities (pad work and heavy bag training) necessitate that boxers have ample recovery periods between bouts of training/exercise if optimal adaptations are to be incurred (Finlay et al., in press). Accordingly, owing to the varying intervention methods and programme designs across previous boxing-related studies, it is likely coaches and boxers do not possess a clear understanding of how to periodise and/or programme their training optimally.

That boxers have to 'make weight' for competition adds further complexity to contest preparation, with acute weight loss (common among boxers) shown to negatively affect training adaptations and physical performance in both training and competition (Hall & Lane, 2001; Morton et al., 2010; Smith et al., 2001). Thus, given the requirements and characteristics of competition, it is imperative future research determines the optimal strategy to periodisation that maximises punch biomechanics and the physical qualities that influence them. Such strategies should also take into account boxer's technical/skill practice, competition schedule and periods of weight loss and/or energy restriction in order to facilitate 'meaningful' training adaptations and adequate recovery between sessions (see Appendix 7).

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Appendix 1

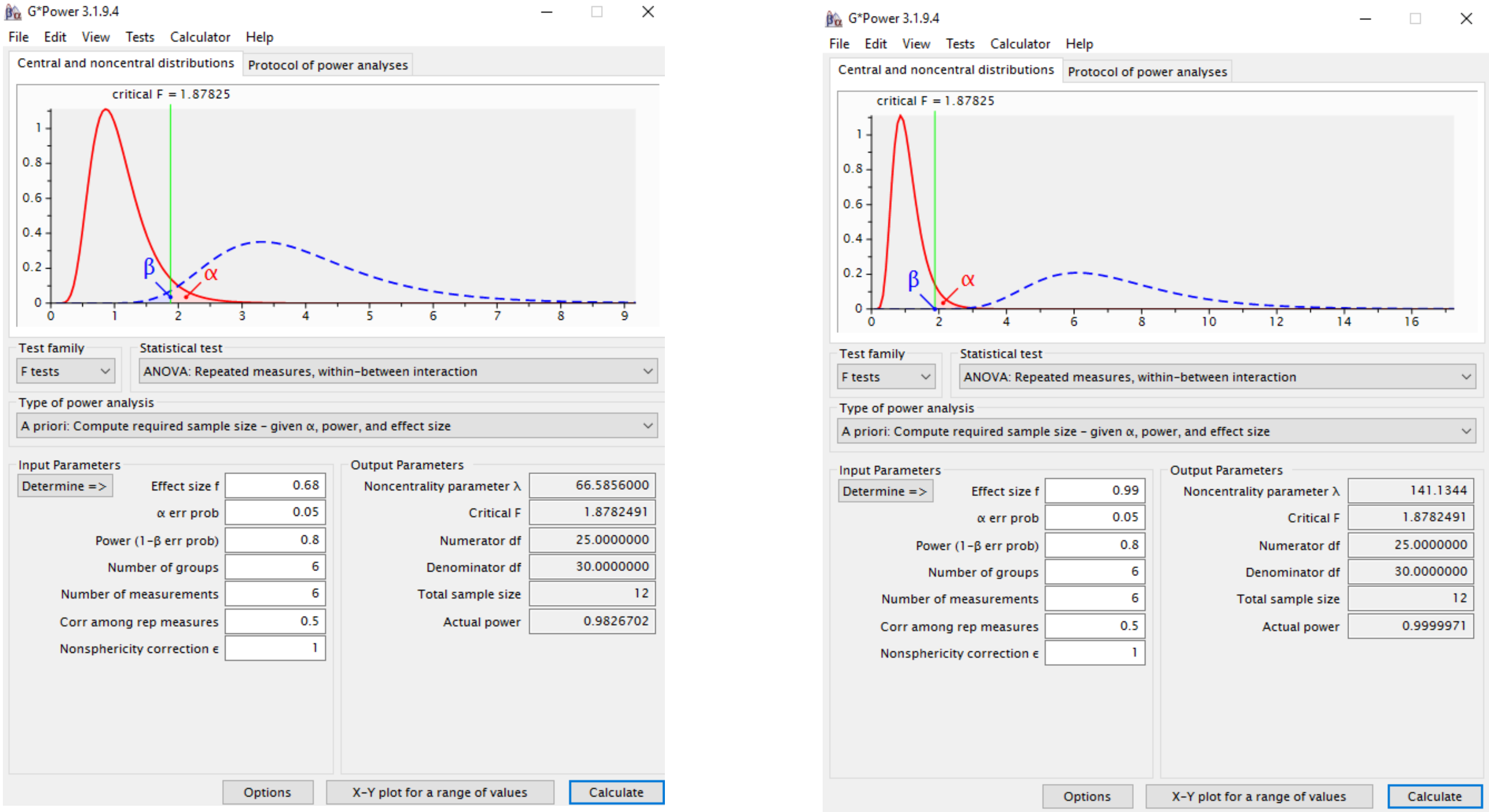

Figure 8.1. G*Power *α priori* sample size calculations informing Chapter 3.

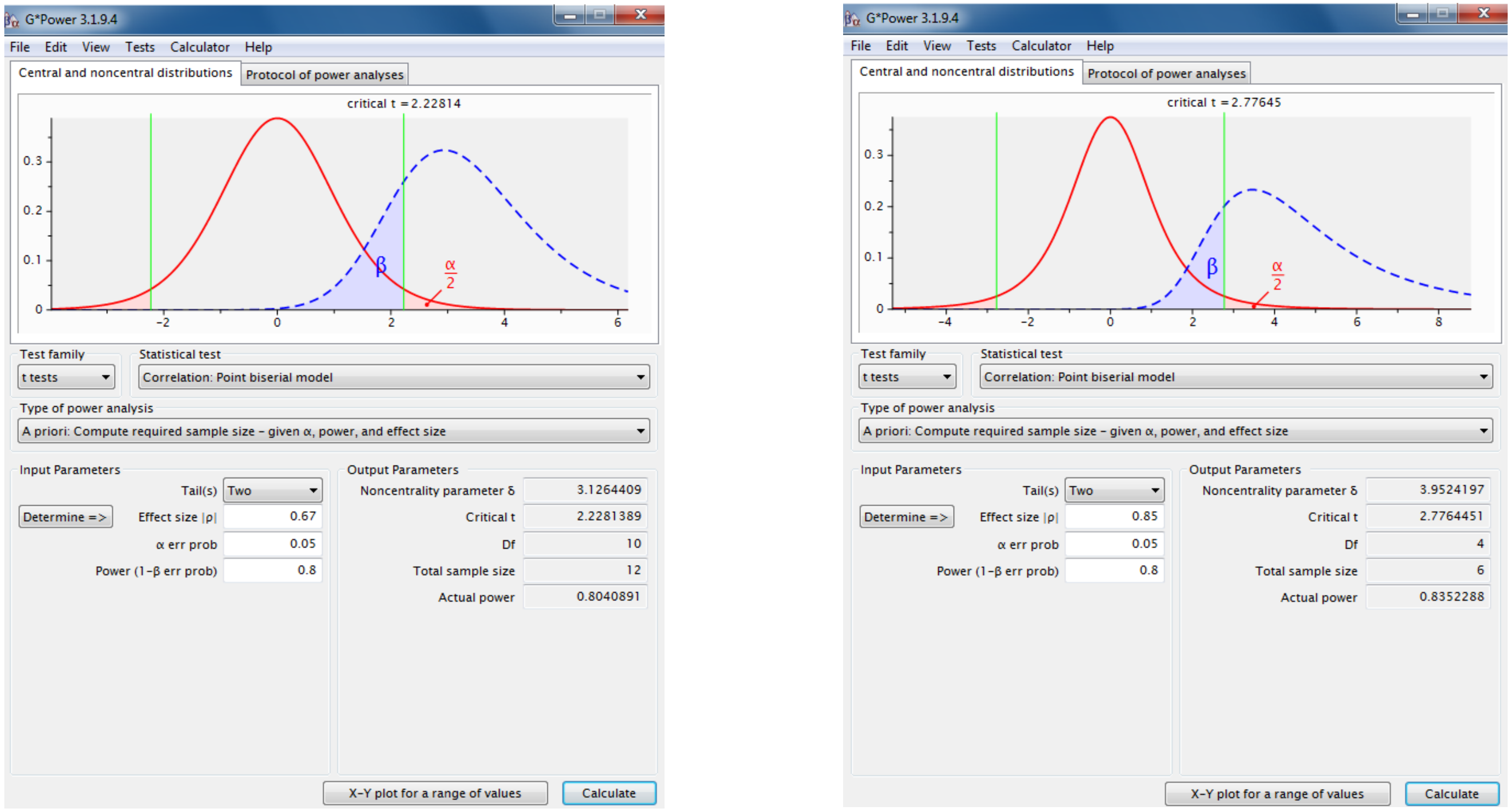

Figure 8.2. G*Power *a priori* sample size calculations informing Chapter 5.

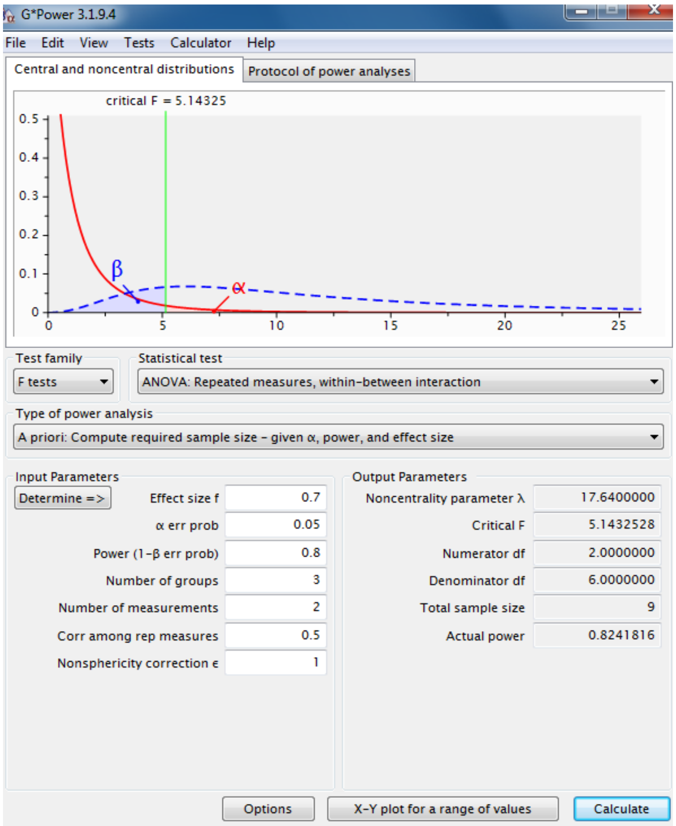

Figure 8.3. G*Power *α priori* sample size calculations informing Chapter 6.

Appendix 2

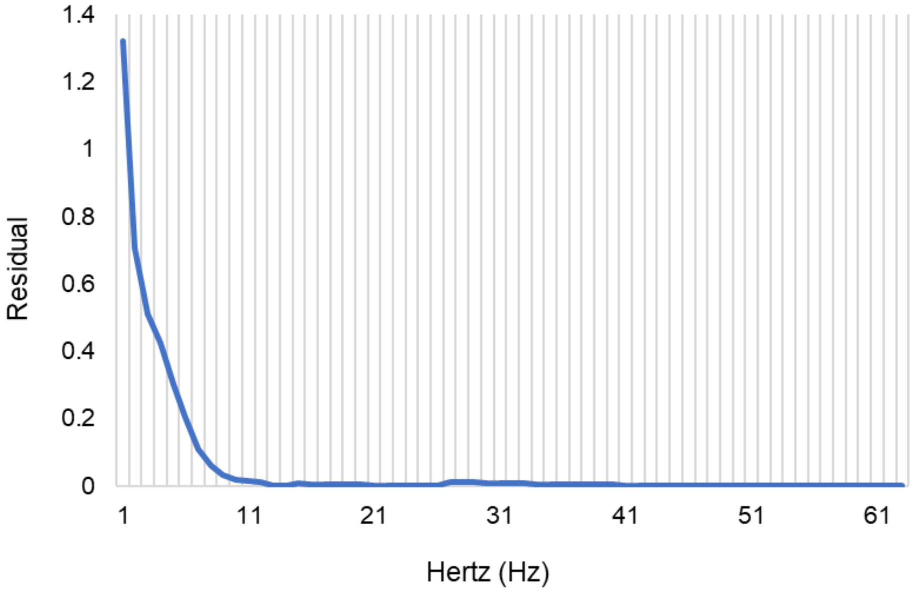

Figure 8.4. Example residual analysis for peak fist velocity of the rear-hand cross.

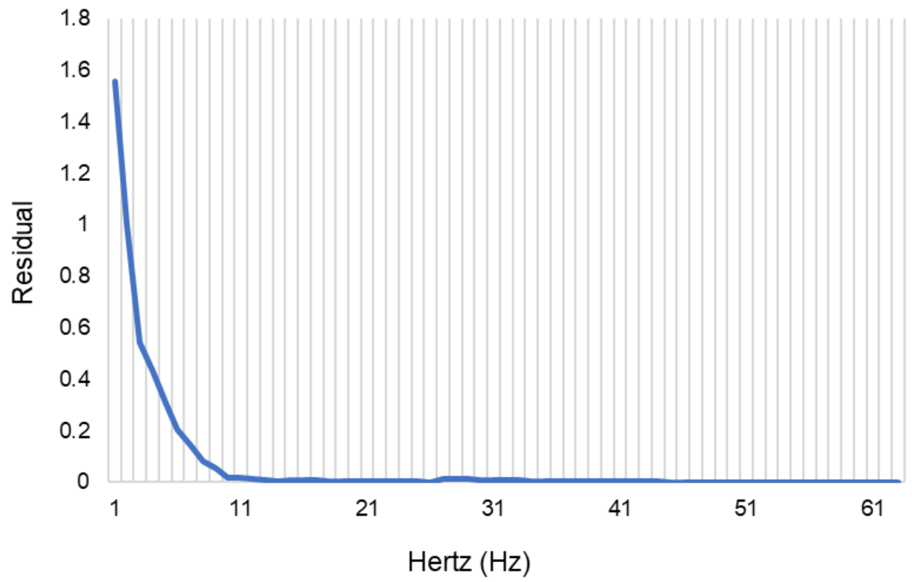

Figure 8.5. Example residual analysis for peak fist velocity of the lead hook.

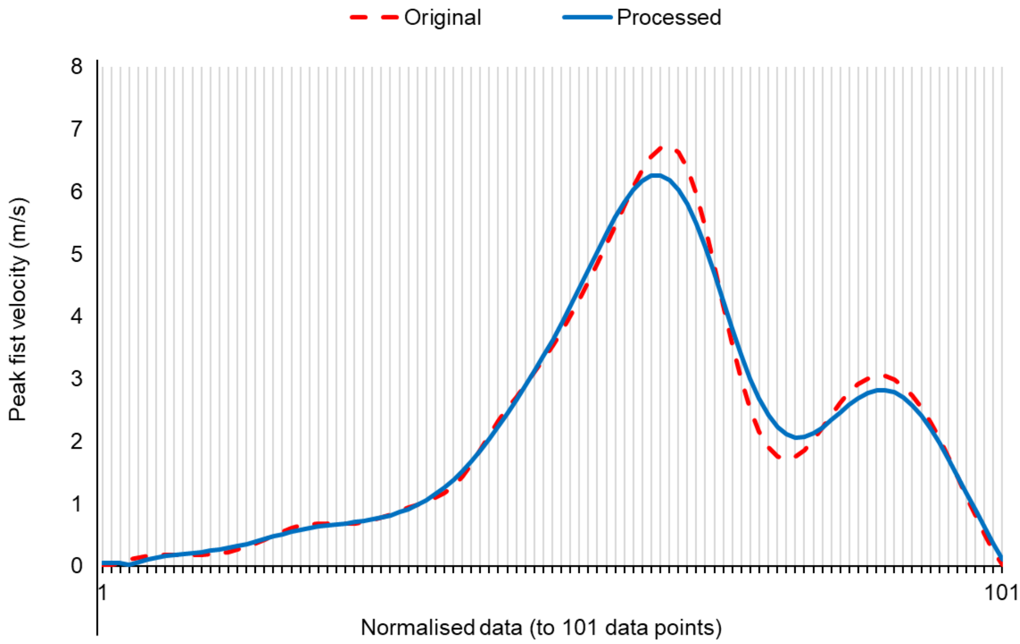

Figure 8.6. Example of motion data processing for peak fist velocity data of a rear-hand cross punch trial.

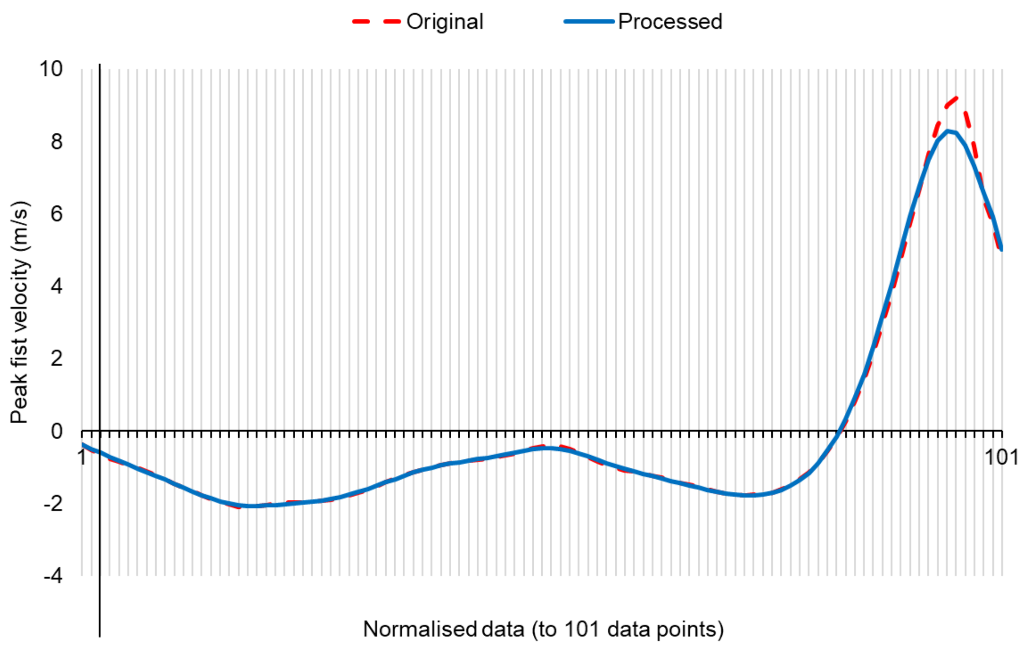

Figure 8.7. Example of motion data processing for peak fist velocity data of a lead hook punch trial.

Appendix 3

Table 8.1. Chapter 4 within-subject and biological variability of delivery time (ms) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	18.4	15.9	9.4	21.5	7.8	17.9	10.2	8.8	5.2	11.9	4.3	9.9
2	13.5	20.9	10.4	27.5	14.3	13.4	7.5	11.6	5.7	15.2	7.9	7.4
3	45.4	35.8	19.7	17.7	12.4	18.3	25.1	19.8	10.9	9.8	6.8	10.1
4	16.0	33.9	12.8	12.7	8.8	13.0	8.9	18.7	7.1	7.0	4.9	7.2
5	17.5	13.1	7.7	18.7	8.0	15.1	9.7	7.2	4.2	10.3	4.4	8.4
6	27.7	25.1	18.1	24.4	4.0	8.6	15.3	13.9	10.0	13.5	2.2	4.8
7	12.1	27.6	11.8	13.8	14.1	6.9	6.7	15.3	6.5	7.6	7.8	3.8
8	17.6	16.8	9.2	14.5	15.1	16.8	9.7	9.3	5.1	8.0	8.4	9.3
9	9.1	24.9	19.3	13.1	15.7	11.8	5.0	13.7	10.7	7.2	8.7	6.5
10	16.5	28.1	10.9	13.2	14.6	11.6	9.1	15.5	6.0	7.3	8.1	6.4
11	24.5	25.0	14.9	24.1	23.3	24.0	13.5	13.8	8.2	13.3	12.9	13.3
12	16.7	15.1	7.8	19.1	7.6	8.0	9.2	8.4	4.3	10.6	4.2	4.4
13	23.0	12.1	8.9	14.7	9.3	14.0	12.7	6.7	4.9	8.1	5.1	7.7
14	8.4	24.6	9.1	14.7	3.5	14.6	4.6	13.6	5.0	8.1	1.9	8.1
15	15.9	7.7	13.0	9.2	11.6	6.6	8.8	4.2	7.2	5.1	6.4	3.6
Mean	18.8	21.8	12.2	17.3	11.3	13.4	10.4	12.0	6.7	9.5	6.3	7.4
SD	9.0	8.1	4.1	5.2	5.1	4.8	5.0	4.5	2.3	2.9	2.8	2.6

Table 8.2. Chapter 4 within-subject and biological variability of peak fist velocity (m/s) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	15.8	7.0	9.4	11.5	11.5	30.0	8.7	3.8	5.2	6.4	6.3	16.6
2	30.6	5.1	9.8	5.6	73.7	19.4	16.9	2.8	5.4	3.1	40.7	10.7
3	13.5	6.8	10.6	10.7	31.4	10.5	7.5	3.8	5.8	5.9	17.3	5.8
4	11.5	10.0	4.8	5.2	2.5	7.9	6.4	5.5	2.6	2.9	1.4	4.4
5	16.0	4.4	10.7	12.5	20.3	36.4	8.9	2.4	5.9	6.9	11.2	20.1
6	13.5	11.0	9.1	9.0	5.2	15.8	7.5	6.1	5.0	5.0	2.8	8.7
7	13.1	5.4	8.9	11.7	25.1	9.9	7.3	3.0	4.9	6.5	13.9	5.5
8	16.8	10.2	12.6	7.7	33.1	5.5	9.3	5.6	7.0	4.3	5.5	3.0
9	7.5	9.8	9.2	6.0	7.2	9.4	4.1	5.4	5.1	3.3	4.0	5.2
10	11.8	6.1	10.4	8.5	17.7	10.1	6.5	3.4	5.7	4.7	9.8	5.6
11	9.5	5.3	7.1	7.5	11.7	9.9	5.3	2.9	3.9	4.1	6.5	5.5
12	12.4	6.8	7.3	8.4	4.2	6.1	6.8	3.8	4.0	4.6	2.3	3.4
13	17.3	6.7	7.2	4.4	13.4	9.0	9.6	3.7	4.0	2.4	7.4	5.0
14	12.7	9.5	6.7	10.3	28.2	26.2	7.0	5.3	3.7	5.7	-2.0	14.5
15	11.7	7.5	6.5	11.3	34.7	8.9	6.5	4.1	3.6	6.2	19.2	4.9
Mean	14.3	7.4	8.7	8.7	19.8	14.3	7.9	4.1	4.8	4.8	9.8	7.9
SD	5.2	2.1	2.0	2.6	18.0	9.4	2.9	1.2	1.1	1.4	10.4	5.2

Table 8.3. Chapter 4 within-subject and biological variability of peak shoulder joint angular velocity (deg/s) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	9.1	14.1	21.6	21.7	9.1	29.7	5.0	7.8	11.9	12.0	5.0	16.4
2	18.8	14.7	15.3	14.6	26.8	6.6	10.4	8.1	8.5	8.1	14.8	3.6
3	17.7	22.1	57.1	24.7	10.1	19.9	9.8	12.2	31.5	13.6	5.6	11.0
4	9.6	12.8	9.7	18.0	8.7	14.3	5.3	7.1	5.4	9.9	4.8	7.9
5	22.2	16.1	16.1	21.3	12.6	14.6	12.3	8.9	8.9	11.8	6.9	8.1
6	33.5	14.4	14.8	15.8	13.7	11.3	18.5	8.0	8.2	8.7	7.6	6.3
7	11.4	42.0	36.8	15.2	5.4	10.4	6.3	23.2	20.3	8.4	3.0	5.8
8	20.8	17.5	17.9	23.1	14.3	17.4	11.5	9.7	9.9	12.8	7.9	9.6
9	47.2	13.9	28.3	24.2	22.8	12.8	26.1	7.7	15.6	13.4	12.6	7.1
10	9.9	16.5	40.0	17.8	21.6	17.9	5.5	9.1	22.1	9.9	11.9	9.9
11	50.1	118.5	7.9	52.9	16.3	10.6	27.7	65.5	4.4	29.3	9.0	5.8
12	15.1	14.8	6.8	15.5	7.0	9.0	8.3	8.2	3.8	8.6	3.9	5.0
13	19.9	45.9	10.7	17.7	6.9	7.9	11.0	25.4	5.9	9.8	3.8	4.4
14	11.8	58.5	19.0	17.3	9.8	24.7	6.5	32.4	10.5	9.6	5.4	13.6
15	12.2	17.2	22.0	17.7	6.4	9.1	6.8	9.5	12.1	9.8	3.5	5.0
Mean	20.6	29.3	21.6	21.2	12.8	14.4	11.4	16.2	11.9	11.7	7.1	8.0
SD	13.1	28.4	13.8	9.4	6.5	6.5	7.2	15.7	7.6	5.2	3.6	3.6

Table 8.4. Chapter 4 within-subject and biological variability of peak elbow joint angular velocity (deg/s) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	15.8	19.3	22.0	27.0	26.1	18.6	8.7	10.7	12.2	14.9	14.4	10.3
2	9.9	5.6	19.3	15.9	29.9	10.9	5.5	3.1	10.7	8.8	16.6	6.0
3	15.6	17.9	12.4	20.0	17.7	38.8	8.6	9.9	6.9	11.0	9.8	21.4
4	19.9	15.9	19.5	17.5	21.1	17.5	11.0	8.8	10.8	9.7	11.7	9.7
5	24.7	28.5	23.8	17.7	22.0	12.4	13.6	15.8	13.2	9.8	12.1	6.9
6	98.8	19.7	31.1	19.2	26.3	13.0	54.6	10.9	17.2	10.6	14.6	7.2
7	37.3	24.0	12.2	31.5	17.5	29.5	20.6	13.2	6.7	17.4	9.6	16.3
8	34.0	59.5	22.6	42.9	16.2	21.7	18.8	32.9	12.5	23.7	9.0	12.0
9	13.2	28.3	42.5	42.7	16.0	26.5	7.3	15.6	23.5	23.6	8.8	14.6
10	26.8	53.8	19.5	35.4	14.6	28.1	14.8	29.7	10.8	19.6	8.1	15.5
11	11.2	29.6	11.7	17.8	15.2	45.6	6.2	16.4	6.5	9.6	8.4	25.2
12	19.4	26.3	22.4	23.3	15.2	15.2	10.7	14.6	12.4	12.9	8.4	8.4
13	23.9	23.0	22.7	26.2	9.4	104.1	13.2	12.7	12.6	14.5	5.2	57.6
14	10.5	29.8	27.2	18.5	18.3	45.4	5.8	16.5	15.1	10.2	10.1	25.1
15	27.5	19.7	16.0	27.5	19.3	15.0	15.2	10.9	8.8	15.2	10.7	8.3
Mean	25.9	26.7	21.7	25.5	19.0	29.5	14.3	14.8	12.0	14.1	10.5	16.3
SD	21.8	13.8	7.9	9.0	5.3	23.7	12.1	7.6	4.4	5.0	2.9	13.1

Table 8.5. Chapter 4 within-subject and biological variability of timing of peak shoulder joint angular velocity (% of punch) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	2.4	16.6	7.9	15.6	0.6	21.8	1.3	9.2	4.4	8.6	0.3	12.0
2	4.3	6.5	5.4	13.5	0.0	0.9	2.4	3.6	3.0	7.5	0.0	0.5
3	26.1	1.4	11.2	0.9	2.0	1.1	14.4	0.8	6.2	0.5	1.1	0.6
4	5.0	8.2	12.5	1.4	0.6	0.7	2.7	4.5	6.9	0.8	0.3	0.4
5	8.8	8.2	9.1	8.1	2.4	2.3	4.9	4.5	5.1	4.5	1.3	1.3
6	7.7	2.0	0.9	0.9	0.6	0.9	4.2	1.1	0.5	0.5	0.3	0.5
7	13.7	14.1	31.5	2.8	0.7	0.9	7.6	7.8	17.4	1.6	0.4	0.5
8	6.7	2.3	11.4	1.3	0.6	0.6	3.7	1.2	6.3	0.7	0.3	0.3
9	25.2	3.0	7.0	1.4	2.7	13.4	13.9	1.6	3.9	0.8	1.5	7.4
10	7.4	6.2	20.9	8.3	11.5	17.0	4.1	3.4	11.6	4.6	6.4	9.4
11	12.4	14.5	1.6	1.3	1.6	1.3	6.9	8.0	0.9	0.7	0.9	0.7
12	1.6	2.2	0	0.9	0.5	0.6	0.9	1.2	0.0	0.5	0.3	0.3
13	2.5	5.0	8.2	1.2	0.7	0.9	1.4	2.8	4.5	0.7	0.4	0.5
14	2.3	5.5	8.0	10.8	0.5	16.5	1.2	3.1	4.4	6.0	0.3	9.1
15	10.7	0.9	27.2	1.6	0.6	0.9	5.9	0.5	15.0	0.9	0.3	0.5
Mean	9.1	6.4	10.9	4.7	1.7	5.3	5.0	3.6	6.0	2.6	0.9	2.9
SD	7.7	5.1	9.2	5.2	2.8	7.6	4.2	2.8	5.1	2.9	1.6	4.2

Table 8.6. Chapter 4 within-subject and biological variability of timing of peak elbow joint angular velocity (% of punch) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	0.6	0.7	1.4	16.9	14.0	8.7	0.3	0.4	0.8	9.3	7.7	4.8
2	5.4	0.0	3.6	5.4	23.3	3.1	3.0	0.0	2.0	3.0	12.9	1.7
3	1.4	2.1	7.5	6.2	6.4	6.6	0.8	1.2	4.1	3.4	3.5	3.7
4	2.1	1.7	15.6	5.4	3.8	6.8	1.1	0.9	8.6	3.0	2.1	3.7
5	3.1	1.2	1.0	4.3	4.7	4.0	1.7	0.7	0.6	2.4	2.6	2.2
6	2.3	1.1	9.7	3.4	8.9	2.9	1.3	0.6	5.4	1.9	4.9	1.6
7	2.1	1.4	15.6	13.9	3.8	6.8	1.1	0.8	8.6	7.7	2.1	3.7
8	0.9	1.0	4.9	13.6	2.0	4.1	0.5	0.6	2.7	7.5	1.1	2.2
9	2.5	1.5	5.1	14.6	7.2	5.6	1.4	0.8	2.8	8.1	4.0	3.1
10	1.3	0.9	6.5	8.3	6.5	8.7	0.7	0.5	3.6	4.6	3.6	4.8
11	0.5	2.6	3.5	24.0	8.3	27.8	0.3	1.4	1.9	13.3	4.6	15.4
12	0.5	0.9	2.7	5.3	2.6	2.2	0.2	0.5	1.5	2.9	1.4	1.2
13	1.2	0.9	4.1	7.0	2.5	27.9	0.6	0.5	2.3	3.9	1.4	15.4
14	0.8	0.6	6.3	0.7	0.8	9.0	0.5	0.3	3.5	0.4	0.5	5.0
15	1.7	0.5	14.3	24.7	3.7	4.2	0.9	0.3	7.9	13.7	2.1	2.3
Mean	1.8	1.1	6.8	10.3	6.6	8.5	1.0	0.6	3.8	5.7	3.6	4.7
SD	1.3	0.6	4.9	7.4	5.7	8.1	0.7	0.4	2.7	4.1	3.2	4.5

Table 8.7. Chapter 4 within-subject and biological variability of peak lead leg GRF (N/s) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	14.1	18.0	7.7	5.2	5.7	8.2	7.8	10.0	4.2	2.9	3.2	4.5
2	32.8	6.4	13.2	5.4	11.6	6.8	18.1	3.5	7.3	3.0	6.4	3.8
3	22.2	11.1	11.1	9.4	14.5	14.9	12.2	6.1	6.1	5.2	8.0	8.2
4	21.2	17.8	5.5	13.1	7.2	10.6	11.7	9.8	3.1	7.3	4.0	5.8
5	58.2	11.5	16.9	14.9	6.8	6.0	32.2	6.3	9.4	8.2	3.8	3.3
6	21.9	18.2	11.5	8.8	7.9	7.8	12.1	10.1	6.4	4.8	4.4	4.3
7	17.1	14.3	5.8	9.8	10.6	9.2	9.4	7.9	3.2	5.4	5.9	5.1
8	21.9	23.2	12.0	10.0	9.6	14.6	12.1	12.8	6.6	5.5	5.3	8.0
9	12.9	10.7	12.1	8.0	7.0	7.3	7.1	5.9	6.7	4.4	3.9	4.0
10	22.5	16.8	13.0	14.1	17.4	6.3	12.4	9.3	7.2	7.8	9.6	3.5
11	36.3	9.8	22.7	9.2	5.3	28.5	20.1	5.4	12.5	5.1	2.9	15.8
12	23.2	21.5	11.6	7.1	8.0	5.1	12.8	11.9	6.4	3.9	4.4	2.8
13	33.1	9.6	17.9	12.2	14.4	10.6	18.3	5.3	9.9	6.7	8.0	5.9
14	12.1	9.0	8.4	6.8	6.0	10.3	6.7	5.0	4.7	3.8	3.3	5.7
15	23.7	7.6	6.7	15.0	7.1	4.7	13.1	4.2	3.7	8.3	3.9	2.6
Mean	24.9	13.7	11.8	9.9	9.3	10.1	13.8	7.6	6.5	5.5	5.1	5.6
SD	11.7	5.2	4.7	3.3	3.7	6.0	6.4	2.9	2.6	1.8	2.0	3.3

Table 8.8. Chapter 4 within-subject and biological variability of peak rear leg GRF (N/s) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	7.2	6.5	18.3	7.6	7.2	12.3	4.0	3.6	10.1	4.2	4.0	6.8
2	10.8	8.4	7.4	3.7	13.6	9.4	6.0	4.6	4.1	2.0	7.5	5.2
3	9.8	10.1	9.3	10.4	9.8	14.7	5.4	5.6	5.1	5.7	5.4	8.1
4	5.2	7.9	12.6	11.8	8.1	22.5	2.9	4.4	7.0	6.5	4.5	12.4
5	12.8	5.9	13.9	14.4	8.2	12.9	7.1	3.3	7.7	7.9	4.5	7.1
6	15.6	10.1	10.3	10.2	12.1	14.9	8.6	5.6	5.7	5.6	6.7	8.3
7	7.6	9.3	35.1	25.5	13.5	12.7	4.2	5.2	19.4	14.1	7.5	7.0
8	17.4	13.5	11.0	7.4	9.0	14.1	9.6	7.5	6.1	4.1	5.0	7.8
9	21.8	21.4	9.8	7.8	6.9	7.8	12.1	11.8	5.4	4.3	3.8	4.3
10	7.1	8.9	15.5	13.3	8.4	11.7	3.9	4.9	8.6	7.4	4.6	6.5
11	16.8	6.0	43.4	6.8	15.3	12.8	9.3	3.3	24.0	3.8	8.5	7.1
12	5.3	9.6	13.8	7.0	6.1	9.4	2.9	5.3	7.6	3.9	3.4	5.2
13	26.5	21.3	17.2	12.6	39.2	5.2	14.6	11.8	9.5	7.0	21.6	2.9
14	6.4	6.5	7.8	4.0	4.4	5.4	3.5	3.6	4.3	2.2	2.4	3.0
15	18.8	9.3	31.4	9.9	17.1	17.1	10.4	5.1	17.4	5.5	9.5	9.5
Mean	12.6	10.3	17.1	10.2	11.9	12.2	7.0	5.7	9.5	5.6	6.6	6.7
SD	6.6	4.9	10.9	5.3	8.4	4.5	3.6	2.7	6.0	2.9	4.6	2.5

Table 8.9. Chapter 4 within-subject and biological variability of lead leg net braking impulse (N/s/kg) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	-79.5	-40.3	-118.3	-34.5	-13.2	-41.9	-43.9	-22.3	-65.4	-19.1	-7.3	-23.14
2	-164.7	-19.9	-38.8	-13.3	-39.9	-7.3	-91.0	-11.0	-21.4	-7.4	-22.1	-4.03
3	-99.5	-57.9	-53.9	-28.9	-49.5	-38.1	-55.0	-32.0	-29.8	-16.0	-27.3	-21.04
4	-49.4	-60.7	-49.1	-20.3	-38.8	-21.7	-27.3	-33.5	-27.2	-11.2	-21.5	-12.01
5	-149.4	-15.4	-43.5	-20.6	-8.5	-32.7	-82.6	-8.5	-24.1	-11.4	-4.7	-18.06
6	-55.0	-42.4	-91.3	-44.8	-20.9	-15.9	-30.4	-23.4	-50.5	-24.7	-11.6	-8.79
7	-65.8	-39.1	-76.4	-15.2	-29.8	-13.9	-36.4	-21.6	-42.2	-8.4	-16.5	-7.66
8	-78.2	-27.2	-79.4	-26.7	-23.4	-19.3	-43.2	-15.0	-43.9	-14.7	-13.0	-10.64
9	-15.7	-34.9	-88.2	-20.5	-50.3	-25.3	-8.7	-19.3	-48.8	-11.3	-27.8	-13.98
10	-45.8	-40.6	-44.4	-21.9	-76.5	-21.2	-25.3	-22.4	-24.6	-12.1	-42.3	-11.71
11	-67.0	-43.0	-59.0	-31.8	-18.3	---	-37.0	-23.7	-15.9	-17.6	-10.1	---
12	-94.0	-28.7	-30.7	-33.6	-20.8	-10.4	-52.0	-15.9	-17.0	-18.6	-11.5	-5.73
13	-111.9	-22.4	-43.6	-30.8	-35.9	-22.5	-41.2	-12.4	8.7	-17.0	-19.8	-12.45
14	-43.8	-35.4	-23.5	-27.5	-18.2	-20.6	-24.2	-19.6	-13.0	-15.2	-10.1	-11.38
15	-108.5	-13.6	-61.3	-21.4	-95.2	-25.9	-60.0	-7.5	-33.9	-11.8	-52.6	-14.31
Mean	-81.9	-34.8	-60.1	-26.1	-36.0	-22.6	-43.9	-19.2	-29.9	-14.4	-19.9	-12.5
SD	40.4	13.9	25.9	8.3	24.1	9.8	21.9	7.7	18.3	4.6	13.3	5.4

Note: --- = Values omitted due to skewed data.

Table 8.10. Chapter 4 within-subject and biological variability of lead leg vertical impulse (N/s/kg) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	19.3	36.3	27.8	37.8	16.4	32.1	10.7	20.1	15.3	20.9	9.1	17.7
2	91.7	37.3	16.0	18.6	34.9	15.3	50.7	20.6	8.9	10.3	19.3	8.5
3	93.9	54.8	40.6	29.0	22.0	35.0	51.9	30.3	22.4	16.0	12.2	19.3
4	37.6	74.7	20.8	21.5	14.6	21.3	20.8	41.3	11.5	11.9	8.1	11.8
5	97.4	16.6	27.2	27.1	13.5	27.0	53.9	9.2	15.0	15.0	7.5	14.9
6	45.4	42.9	31.3	48.2	10.5	16.9	25.1	23.7	17.3	26.6	5.8	9.3
7	34.3	47.1	22.9	16.7	24.5	14.8	19.0	26.0	12.6	9.2	13.5	8.2
8	44.4	27.4	17.4	23.6	33.4	29.7	24.5	15.2	9.6	13.0	18.5	16.4
9	8.3	35.0	31.2	22.6	36.8	22.3	4.6	19.3	17.2	12.5	20.3	12.3
10	26.5	43.1	22.6	17.1	34.4	26.6	14.6	23.8	12.5	9.5	19.0	14.7
11	57.8	39.5	40.0	39.1	34.1	---	32.0	21.9	22.1	21.6	18.9	---
12	38.3	26.4	20.8	37.3	18.4	18.6	21.2	14.6	11.5	20.6	10.2	10.3
13	77.2	26.1	22.2	32.3	13.7	22.5	42.7	14.4	12.3	17.8	7.6	12.4
14	37.8	41.7	13.3	34.1	8.7	23.1	20.9	23.0	7.4	18.8	4.8	12.8
15	72.4	15.3	53.9	23.2	58.1	13.9	40.0	8.5	29.8	12.8	32.1	7.7
Mean	52.2	37.6	27.2	28.5	24.9	22.8	28.8	20.8	15.0	15.8	13.8	12.6
SD	28.2	15.0	10.9	9.3	13.5	6.6	15.6	8.3	6.0	5.1	7.4	3.7

Note: --- = Values omitted due to skewed data.

Table 8.11. Chapter 4 within-subject and biological variability of rear leg net propulsive impulse (N/s/kg) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	34.5	33.8	38.0	53.9	28.3	39.6	19.1	18.7	21.0	29.8	15.6	21.9
2	21.7	42.6	23.6	22.4	29.8	15.8	12.0	23.6	13.0	12.4	16.5	8.7
3	111.2	72.6	38.6	42.7	38.6	51.3	61.5	40.1	21.3	23.6	21.4	28.4
4	34.9	65.8	84.8	26.1	12.9	36.6	19.3	36.4	46.9	14.4	7.1	20.2
5	59.4	35.1	55.1	44.8	20.9	36.8	32.8	19.4	30.4	24.8	11.5	20.3
6	56.1	53.0	64.9	48.6	14.8	12.1	31.0	29.3	35.9	26.9	8.2	6.7
7	76.1	51.4	96.3	30.4	46.6	14.7	42.0	28.4	53.2	16.8	25.8	8.1
8	20.6	36.9	30.8	26.1	25.9	27.8	11.4	20.4	17.0	14.4	14.3	15.4
9	47.4	64.4	89.2	24.5	25.6	22.7	26.2	35.6	49.3	13.5	14.1	12.6
10	39.4	53.6	33.0	34.1	31.5	26.1	21.8	29.6	18.2	18.8	17.4	14.4
11	47.7	65.8	28.9	48.0	80.7	---	26.4	36.4	16.0	26.5	44.6	---
12	44.1	32.3	12.3	34.6	20.8	13.9	24.4	17.8	6.8	19.1	11.5	7.7
13	38.5	21.6	70.0	25.3	55.8	23.4	21.3	11.9	38.7	14.0	30.8	13.0
14	19.6	45.4	37.1	23.6	9.5	33.6	10.8	25.1	20.5	13.0	5.3	18.6
15	58.3	30.1	16.4	33.7	56.8	64.8	32.2	16.6	9.1	18.6	31.4	35.8
Mean	47.3	47.0	47.9	34.6	33.2	29.9	26.1	26.0	26.5	19.1	18.4	16.6
SD	23.7	15.5	27.1	10.5	19.5	15.2	13.1	8.6	15.0	5.8	10.8	8.4

Note: --- = Values omitted due to skewed data.

Table 8.12. Chapter 4 within-subject and biological variability of rear leg vertical impulse (N/s/kg) across punch techniques.

	Within-subject coefficient of variation (mean CV%)						Biological coefficient of variation (BCV%)					
	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut	Jab	Rear-hand cross	Lead hook	Rear hook	Lead Uppercut	Rear Uppercut
Boxer												
1	4.2	31.5	12.4	51.3	18.7	42.5	2.3	17.4	6.8	28.3	10.3	23.5
2	24.2	49.7	3.7	26.1	30.6	13.1	13.4	27.5	2.0	14.4	16.9	7.2
3	103.4	75.1	46.3	37.4	28.2	51.4	57.1	41.5	25.6	20.7	15.6	28.4
4	31.1	71.9	34.5	26.2	20.1	32.0	17.2	39.8	19.1	14.5	11.1	17.7
5	43.7	34.0	29.7	57.6	22.9	28.1	24.2	18.8	16.4	31.8	12.6	15.5
6	48.1	58.4	32.0	56.4	5.9	13.2	26.6	32.3	17.7	31.2	3.3	7.3
7	32.4	55.1	22.4	33.3	31.7	15.3	17.9	30.4	12.4	18.4	17.5	8.5
8	23.5	36.7	16.1	35.3	27.3	29.5	13.0	20.3	8.9	19.5	15.1	16.3
9	46.9	57.5	40.0	26.8	31.0	25.9	25.9	31.8	22.1	14.8	17.1	14.3
10	34.6	56.8	17.4	34.4	26.3	23.0	19.1	31.4	9.6	19.0	14.5	12.7
11	51.5	65.7	52.9	53.3	57.2	---	28.5	36.3	29.2	29.4	31.6	---
12	30.5	37.2	13.0	37.1	18.9	12.6	16.8	20.6	7.2	20.5	10.5	7.0
13	36.2	24.8	41.3	28.6	45.8	26.4	20.0	13.7	22.8	15.8	25.3	14.6
14	23.7	51.1	28.2	24.7	9.3	30.1	13.1	28.2	15.6	13.6	5.1	16.6
15	50.8	35.6	59.1	43.5	10.9	57.4	28.1	19.7	32.7	24.1	6.6	31.7
Mean	39.0	49.4	29.9	38.1	25.6	28.6	21.6	27.3	16.5	21.1	14.2	15.8
SD	21.9	15.4	16.0	11.6	13.4	13.9	12.1	8.5	8.9	6.4	7.4	7.7

Note: --- = Values omitted due to skewed data.

Appendix 4

Table 8.13. Chapter 6 worthwhile change statistics for kinetic and kinematic variables across punch techniques.

	Jab			**Rear-hand cross**			**Lead hook**			**Rear hook**			**Lead uppercut**			**Rear uppercut**		
	SWC %	**MWC %**	**LWC %**	**SWC %**	**MWC %**	**LWC %**	**SWC %**	**MWC %**	**LWC %**	**SWC %**	**MWC %**	**LWC %**	**SWC %**	**MWC %**	**LWC %**	**SWC %**	**MWC %**	**LWC %**
DT	3.9	11.7	23.4	4.2	12.5	24.9	2.9	8.8	17.5	3.2	9.7	19.4	2.5	7.4	14.8	2.8	8.5	16.9
FV	1.4	4.1	8.3	2.3	6.8	13.5	2.2	6.7	13.4	2.1	6.3	12.5	3.2	9.7	19.4	3.0	9.0	18.1
SJAV	2.5	7.4	14.8	2.5	7.5	15.0	3.6	10.8	21.5	3.6	10.9	21.8	2.3	6.8	13.6	1.9	5.7	11.3
EJAV	3.7	11.1	22.1	6.0	18.1	36.1	2.9	8.7	17.3	3.8	11.3	22.6	3.7	11.0	22	3.7	11.2	22.4
LLGRF	4.9	14.6	29.3	2.9	8.7	17.4	3.1	9.3	18.6	1.9	5.6	11.1	3.9	11.6	23.2	3.7	11.0	22.0
RLGRF	2.1	6.2	12.3	1.9	5.6	11.3	2.2	6.6	13.2	2.5	7.6	15.2	2.7	8.1	16.2	2.2	6.5	12.9
LLFyI	13.8	41.4	82.8	10.8	32.4	64.9	10.8	32.3	64.7	6.9	20.7	41.4	10.4	31.2	62.5	5.9	17.7	35.4
LLFzI	11.5	34.4	68.7	14.4	43.3	86.6	8.2	24.5	49.0	10.5	31.4	62.8	7.1	21.2	42.3	8.9	26.8	53.7
RLFyI	6.2	18.6	37.1	9.9	29.7	59.4	8.8	26.4	52.9	6.3	18.9	37.9	7.9	23.8	47.6	6.5	19.5	39.0
RLFzI	6.5	19.5	39.1	9.9	29.8	59.7	7.6	22.9	45.9	8.2	24.6	49.2	6.6	19.7	39.4	8.4	25.2	50.3

SWC% = small worthwhile change, MWC% = moderate worthwhile change, LWC% = large worthwhile change, DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse

Appendix 5

Table 8.14. Chapter 6 control group pre-to-post intervention performance change percentages (%) and Cohen's *d* (95% confidence intervals) for kinematic and kinetic variable values across punch types.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
DT	-0.3% 0.03 (-1.21 to 1.27)	+0.3% 0.02 (-1.22 to 1.26)	+0.9% 0.1 (-1.15 to 1.33)	-0.4% 0.03 (-1.21 to 1.27)	-1.0% 0.1 (-1.15 to 1.33)	-1.0% 0.1 (-1.15 to 1.33)
FV	+0.7% 0.3 (-0.97 to 1.52)	+1.1% 0.1 (-1.15 to 1.33)	+0.5% 0.1 (-1.15 to 1.33)	+0.7% 0.1 (-1.15 to 1.33)	+0.7% 0.1 (-1.15 to 1.33)	+0.5% 0.03 (-1.21 to 1.27)
SJAV	+1.5% 0.1 (-1.15 to 1.33)	+7.3% 0.5 (-0.80 to 1.71)	+1.2% 0.2 (-1.06 to 1.42)	+3.1% 0.1 (-1.15 to 1.33)	+1.8% 0.2 (-1.06 to 1.42)	+1.6% 0.1 (-1.15 to 1.33)
EJAV	+2.4% 0.2 (-1.06 to 1.42)	+4.1% 0.1 (-1.15 to 1.33)	+3.8% 0.2 (-1.06 to 1.42)	+3.3% 0.1 (-1.15 to 1.33)	+3.9% 0.03 (-1.21 to 1.27)	+2.0% 0.1 (-1.15 to 1.33)
LLGRF	-5.5% 0.2 (-1.06 to 1.42)	+19.0% 1.2 (-0.24 to 2.41)	+14.4% 1.5 (-0.02 to 2.73)	+2.6% 0.4 (-0.89 to 1.61)	+6.2% 0.4 (-0.89 to 1.61)	+15.3% 1.4 (-0.09 to 2.62)
RLGRF	+5.9% 0.5 (-0.80 to 1.71)	-7.7% 0.7 (-0.64 to 1.90)	-3.2% 0.2 (-1.06 to 1.42)	+3.7% 0.5 (-0.80 to 1.71)	+4.8% 0.3 (-0.97 to 1.52)	+2.2% 0.2 (-1.06 to 1.42)
LLFyI	+11.8% 0.1 (-1.15 to 1.33)	-0.1% 0.03 (-1.21 to 1.27)	+28.5% 0.3 (-0.97 to 1.52)	+4.5% 0.1 (-1.15 to 1.33)	+6.4% 0.1 (-1.15 to 1.33)	-18.6% 0.7 (-0.64 to 1.90)
LLFzI	-37.5% 0.9 (-0.48 to 2.10)	+10.4% 0.4 (-0.89 to 1.61)	+40.5% 0.7 (-0.64 to 1.90)	+28.0% 0.5 (-0.80 to 1.71)	+34.8% 0.8 (-0.56 to 2.00)	-7.7% 0.10.1 (-1.15 to 1.33)
RLFyI	-24.7% 0.7 (-0.64 to 1.90)	-2.7% 0.1 (-1.15 to 1.33)	-14.1% 0.3 (-0.97 to 1.52)	-6.0% 0.2 (-1.06 to 1.42)	-13.8% 0.4 (-0.89 to 1.61)	-23.7% 1.0 (-0.40 to 2.20)
RLFzI	-32.2% 1.0 (-0.40 to 2.20)	-11.0% 0.3 (-0.97 to 1.52)	-6.1% 0.2 (-1.06 to 1.42)	-4.4% 0.1 (-1.15 to 1.33)	-6.1% 0.2 (-1.06 to 1.42)	-25.0% 0.7 (-0.64 to 1.90)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse

Table 8.15. Chapter 6 strength group pre-to-post intervention performance change percentages (%) and Cohen's *d* (95% confidence intervals) for kinematic and kinetic variable values across punch types.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
DT	-10% 0.5 (-0.80 to 1.71)	-10.1% 0.6 (-0.72 to 1.80)	-7.7% 0.6 (-0.72 to 1.80)	-7.9% 0.7 (-0.64 to 1.90)	-8.1% 1.2 (-0.24 to 2.41)	-7.2% 1.6 (0.05 to 2.84)
FV	+7.1% 1.0 (-0.40 to 2.20)	+11.3% 1.2 (-0.24 to 2.41)	+12.9% 1.6 (0.05 to 2.84)	+11.5% 1.5 (-0.02 to 2.73)	+12.8% 0.8 (-0.56 to 2.00)	+12.7% 1.0 (-0.40 to 2.20)
SJAV	+10.3% 1.2 (-0.24 to 2.41)	+25.7% 0.9 (-0.48 to 2.10)	+27.7% 1.4 (-0.09 to 2.62)	+26.5% 1.6 (0.05 to 2.84)	+21.6% 1.5 (-0.02 to 2.73)	+17.2% 1.6 (0.05 to 2.84)
EJAV	+21.7% 1.4 (-0.09 to 2.62)	+23.4% 0.8 (-0.56 to 2.00)	+27.8% 1.7 (0.12 to 2.94)	+25.6% 1.4 (-0.09 to 2.62)	+40.9% 1.6 (0.05 to 2.84)	+37.4% 1.2 (-0.24 to 2.41)
LLGRF	+18.3% 0.6 (-0.72 to 1.80)	+47.1% 1.4 (-0.09 to 2.62)	+11.6% 0.7 (-0.64 to 1.90)	+40.0% 1.6 (0.05 to 2.84)	+35.7% 1.6 (0.05 to 2.84)	+40.8% 1.3 (-0.17 to 2.52)
RLGRF	+42.8% 1.6 (0.05 to 2.84)	+11.3% 0.9 (-0.48 to 2.10)	+32.7% 1.4 (-0.09 to 2.62)	+11.7% 1.0 (-0.40 to 2.20)	+26.9% 1.3 (-0.17 to 2.52)	+26.9% 1.0 (-0.40 to 2.20)
LLFyI	-57.0% 1.7 (0.12 to 2.94)	-14.0% 0.3 (-0.97 to 1.52)	-36.5% 1.6 (0.05 to 2.84)	-31.2% 0.7 (-0.64 to 1.90)	-74.9% 1.8 (0.20 to 3.05)	-21.4% 0.6 (-0.72 to 1.80)
LLFzI	-71.3% 1.6 (0.05 to 2.84)	-51.5% 1.5 (-0.02 to 2.73)	-57.2% 1.2 (-0.24 to 2.41)	-62.4% 1.3 (-0.17 to 2.52)	-64.9% 1.6 (0.05 to 2.84)	-43.4% 1.4 (-0.09 to 2.62)
RLFyI	-59.5% 1.4 (-0.09 to 2.62)	-54.9% 1.2 (-0.24 to 2.41)	-64.1% 1.7 (0.12 to 2.94)	-39.9% 0.9 (-0.48 to 2.10)	-74.7% 1.7 (0.12 to 2.94)	-40.3% 1.0 (-0.40 to 2.20)
RLFzI	-42.5% 1.0 (-0.40 to 2.20)	-72.3% 1.5 (-0.02 to 2.73)	-53.4% 1.2 (-0.24 to 2.41)	-61.8% 1.3 (-0.17 to 2.52)	-62.3% 1.6 (0.05 to 2.84)	-63.6% 1.5 (-0.02 to 2.73)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse

Table 8.16. Chapter 6 contrast group pre-to-post intervention performance change percentages (%) and Cohen's *d* (95% confidence intervals) for kinematic and kinetic variable values across punch types.

	Jab	**Rear-hand cross**	**Lead hook**	**Rear hook**	**Lead uppercut**	**Rear uppercut**
DT	-16.0% 1.0 (-0.40 to 2.20)	-13.3% 0.7 (-0.64 to 1.90)	-11.0% 0.6 (-0.72 to 1.80)	-10.9% 0.5 (-0.80 to 1.71)	-10.4% 0.6 (-0.72 to 1.80)	-11.5% 0.5 (-0.80 to 1.71)
FV	+17.2% 1.3 (-0.17 to 2.52)	+13.1 1.0 (-0.40 to 2.20)	+15.5 1.3 (-0.17 to 2.52)	+11.1 1.1 (-0.32 to 2.31)	+14.6 1.0 (-0.40 to 2.20)	+12.7 0.8 (-0.56 to 2.00)
SJAV	+14.8% 0.9 (-0.48 to 2.10)	+42.6% 1.6 (0.05 to 2.84)	+27.9% 1.2 (-0.24 to 2.41)	+38.0% 1.5 (-0.02 to 2.73)	+26.0% 1.6 (0.05 to 2.84)	+20.9% 1.5 (-0.02 to 2.73)
EJAV	+29.8% 1.2 (-0.24 to 2.41)	+39.1% 1.2 (-0.24 to 2.41)	+54.6% 1.8 (0.20 to 3.05)	+40.2% 1.5 (-0.02 to 2.73)	+53.8% 1.6 (0.05 to 2.84)	+47.6% 1.5 (-0.02 to 2.73)
LLGRF	+42.7% 0.9 (-0.48 to 2.10)	+146.1% 1.9 (0.27 to 3.16)	+30.3% 1.2 (-0.24 to 2.41)	+79.1% 1.7 (0.12 to 2.94)	+42.2% 1.5 (-0.02 to 2.73)	+72.0% 1.7 (0.12 to 2.94)
RLGRF	+75.6% 1.6 (0.05 to 2.84)	+28.4% 1.0 (-0.40 to 2.20)	+75.8% 1.5 (-0.02 to 2.73)	+14.3% 1.0 (-0.40 to 2.20)	+50.1% 1.7 (0.12 to 2.94)	+51.4% 1.8 (0.20 to 3.05)
LLFyI	-12.6% 1.7 (0.12 to 2.94)	-16.6% 0.4 (-0.89 to 1.61)	-43.9% 1.7 (0.12 to 2.94)	-24.8% 1.0 (-0.40 to 2.20)	-58.8% 1.7 (0.12 to 2.94)	-29.4% 1.7 (0.12 to 2.94)
LLFzI	-76.4% 1.2 (-0.24 to 2.41)	-59.0% 0.9 (-0.48 to 2.10)	-48.7% 1.5 (-0.02 to 2.73)	-64.0% 1.1 (-0.32 to 2.31)	-69.6% 1.7 (0.12 to 2.94)	-61.0% 1.4 (-0.09 to 2.62)
RLFyI	-83.5% 1.6 (0.05 to 2.84)	-60.5% 1.2 (-0.24 to 2.41)	-82.3% 1.5 (-0.02 to 2.73)	-38.6% 1.5 (-0.02 to 2.73)	-84.7% 1.5 (-0.02 to 2.73)	-42.7% 1.7 (0.12 to 2.94)
RLFzI	-57.6% 1.6 (0.05 to 2.84)	-81.9% 1.4 (-0.09 to 2.62)	-70.7% 1.6 (0.05 to 2.84)	-69.3% 1.4 (-0.09 to 2.62)	-66.8% 1.5 (-0.02 to 2.73)	-71.7% 1.6 (0.05 to 2.84)

DT = delivery time, FV = peak resultant fist velocity, SJAV = peak shoulder joint resultant angular velocity, EJAV = peak elbow joint resultant angular velocity, LLGRF = peak lead leg resultant GRF, RLGRF = peak rear leg resultant GRF, LLFyI = lead leg net braking impulse, LLFzI = lead leg vertical impulse, RLFyI = rear leg net propulsive impulse, RLFzI = rear leg vertical impulse

Appendix 6

Table 8.17. Chapter 6 individual boxer punch delivery time performance changes from pre-to-post intervention.

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
Group (participant)	**Pre (ms)**	**Post (ms)**	**Pre (ms)**	**Post (ms)**	**Pre (ms)**	**Post (ms)**	**Pre (ms)**	**Post (ms)**	**Pre (ms)**	**Post (ms)**	**Pre (ms)**	**Post (ms)**
Control												
1	337	334	434	425	592	584	541	535	649	643	617	610
2	266	260	313	310	452	444	480	478	507	504	581	574
3	285	280	352	374	599	600	622	614	675	672	789	784
4	268	283	344	341	689	682	667	660	681	676	653	648
5	317	312	373	370	611	606	565	576	569	554	611	602
Mean ± SD	295 ± 31.3	294 ± 29.1	363 ± 45.0	364 ± 42.8	589 ± 85.7	583 ± 86.5	575 ± 72.3	573 ± 70.2	616 ± 75.7	610 ± 76.9	650 ± 81.8	644 ± 82.8
Strength												
1	465	432	572	534	693	644	643	602	695	652	640	602
2	321	280	393	340	679	630	677	626	675	632	605	554
3	346	298	428	378	634	580	661	610	704	620	623	582
4	325	278	405	354	488	441	498	442	639	582	611	564
5	472	448	544	500	699	652	635	588	735	682	607	561
Mean ± SD	386 ± 76.2	347 ± 85.3	468 ± 83.5	421 ± 89.3	638 ± 87.8	589 ± 87.4	623 ± 71.8	574 ± 74.8	690 ± 35.6	634 ± 37.2	617 ± 14.6	573 ± 19.5
Contrast												
1	401	322	495	426	675	606	613	532	662	600	609	542
2	393	340	603	535	625	546	529	470	620	528	535	478
3	280	232	362	298	471	405	381	318	455	408	376	312
4	381	322	419	370	659	590	643	582	709	644	633	570
5	437	374	543	472	769	700	763	708	719	658	698	622
Mean ± SD	379 ± 58.8	318 ± 52.6	484 ± 95.9	420 ± 91.2	640 ± 108.1	569 ± 107.6	586 ± 142.2	522 ± 143.7	633 ± 107.1	568 ± 102.6	570 ± 123.3	505 ± 119.6

SD = standard deviation, ms = milliseconds

Table 8.18. Chapter 6 individual boxer peak fist velocity performance changes from pre-to-post intervention.

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
Group (participant)	**Pre (m/s)**	**Post (m/s)**	**Pre (m/s)**	**Post (m/s)**	**Pre (m/s)**	**Post (m/s)**	**Pre (m/s)**	**Post (m/s)**	**Pre (m/s)**	**Post (m/s)**	**Pre (m/s)**	**Post (m/s)**
Control												
1	5.76	5.76	6.26	6.30	9.85	9.92	9.49	9.50	7.73	7.86	7.65	7.71
2	5.05	5.08	5.62	5.70	9.42	9.45	8.78	8.86	7.82	7.89	8.11	8.21
3	5.33	5.38	5.66	5.71	8.54	8.58	8.25	8.35	7.95	7.98	10.17	10.14
4	5.53	5.59	6.07	6.15	10.13	10.14	10.46	10.57	9.39	9.41	10.89	10.95
5	4.96	5.01	5.01	5.09	9.84	9.94	8.72	8.75	8.51	8.56	9.76	9.79
Mean ± SD	5.33 ± 0.33	5.36 ± 0.32	5.72 ± 0.48	5.79 ± 0.47	9.56 ± 0.62	9.61 ± 0.63	9.14 ± 0.86	9.21 ± 0.87	8.28 ± 0.69	8.34 ± 0.66	9.32 ± 1.38	9.36 ± 1.36
Strength												
1	5.08	6.32	6.37	6.87	10.30	11.24	8.87	9.99	7.43	9.09	9.10	9.98
2	5.32	5.67	5.24	6.17	9.56	10.78	9.29	10.59	10.45	11.52	11.52	13.46
3	5.73	6.31	6.63	7.19	10.24	11.73	10.09	10.97	11.15	12.33	10.04	11.23
4	6.26	5.67	5.96	6.66	9.72	10.73	9.64	10.69	8.27	9.34	9.35	10.39
5	5.49	5.89	5.83	6.55	10.17	11.97	9.05	10.08	9.75	10.78	10.09	11.41
Mean ± SD	5.58 ± 0.45	5.97 ± 0.33	6.01 ± 0.54	6.69 ± 0.38	10.00 ± 0.33	11.29 ± 0.55	9.39 ± 0.49	10.46 ± 0.42	9.41 ± 1.54	10.61 ± 1.39	10.02 ± 0.94	11.30 ± 1.35
Contrast												
1	5.75	5.93	5.61	6.61	10.15	12.95	10.04	11.22	9.10	10.65	9.24	11.69
2	5.22	6.09	6.08	6.84	10.42	12.28	10.12	11.19	9.64	10.91	9.40	10.47
3	5.67	6.54	6.41	7.25	12.45	13.75	11.39	12.68	12.00	13.68	12.79	13.89
4	5.01	6.84	7.41	8.37	11.10	12.82	10.00	11.33	10.28	12.20	11.92	13.16
5	5.28	6.14	7.43	8.19	13.16	14.37	12.02	13.11	12.08	13.40	12.75	14.00
Mean ± SD	5.38 ± 0.31	6.31 ± 0.37	6.59 ± 0.81	7.45 ± 0.79	11.45 ± 1.30	13.24 ± 0.83	10.71 ± 0.93	11.91 ± 0.91	10.62 ± 1.36	12.17 ± 1.39	11.22 ± 1.77	12.64 ± 1.52

SD = standard deviation, m/s = metres per second

Table 8.19. Chapter 6 individual boxer peak angular shoulder velocity performance changes from pre-to-post intervention.

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
Group (participant)	**Pre (deg/s)**	**Post (deg/s)**	**Pre (deg/s)**	**Post (deg/s)**	**Pre (deg/s)**	**Post (deg/s)**	**Pre (deg/s)**	**Post (deg/s)**	**Pre (deg/s)**	**Post (deg/s)**	**Pre (deg/s)**	**Post (deg/s)**
Control												
1	656.12	662.36	475.44	588.78	675.92	680.38	655.76	660.27	1079.00	1092.99	1100.22	1123.75
2	495.63	509.73	410.81	381.90	716.77	739.97	635.06	644.18	849.81	867.13	901.13	901.14
3	552.06	561.20	523.39	601.59	509.01	501.23	536.84	611.75	855.75	871.50	911.78	930.40
4	533.63	537.33	507.41	516.04	699.10	708.28	760.61	762.48	715.23	719.51	900.29	918.80
5	507.34	516.42	457.00	459.71	738.04	747.42	816.61	830.37	818.24	845.56	853.28	867.65
Mean ± SD	548.96 ± 63.84	557.41 ± 62.02	474.81 ± 44.26	509.60 ± 91.61	667.77 ± 91.64	675.46 ± 100.99	680.98 ± 109.84	701.81 ± 91.33	863.61 ± 132.97	879.34 ± 134.67	933.34 ± 95.99	948.35 ± 100.87
Strength												
1	545.70	624.56	449.48	478.95	680.40	973.04	694.30	940.00	1026.78	1188.03	1014.16	1220.67
2	614.38	653.63	447.76	566.75	613.61	760.50	626.26	819.46	828.65	993.09	900.37	1024.50
3	638.90	700.24	597.05	851.30	586.00	704.76	749.32	896.42	913.29	1068.55	941.67	1098.83
4	538.72	597.16	620.26	736.66	538.19	688.09	769.27	997.32	891.85	1079.61	933.73	1115.58
5	601.87	667.02	417.07	548.44	588.17	712.12	750.17	889.04	903.48	1219.18	990.80	1144.76
Mean ± SD	587.91 ± 43.87	648.52 ± 39.55	506.32 ± 94.65	636.42 ± 152.98	601.28 ± 51.96	767.70 ± 117.90	717.86 ± 58.36	908.45 ± 65.83	912.81 ± 71.76	1109.69 ± 92.62	956.15 ± 45.80	1120.87 ± 71.30
Contrast												
1	609.71	685.70	458.04	615.84	706.18	912.77	745.70	1082.58	874.90	1126.33	913.02	1152.33
2	616.73	711.47	487.17	607.83	760.06	940.28	802.01	1197.23	940.83	1157.91	1001.97	1238.94
3	472.91	570.95	566.59	751.87	724.72	967.96	864.52	1183.82	1042.15	1325.22	1127.28	1350.52
4	633.46	729.00	494.25	811.47	634.69	859.10	776.99	1100.15	931.22	1208.32	1026.92	1270.66
5	743.84	836.04	473.88	748.43	1027.87	1246.79	1145.98	1417.87	1084.76	1324.73	1157.05	1306.57
Mean ± SD	615.33 ± 96.38	706.63 ± 95.02	495.99 ± 41.82	707.09 ± 90.54	770.70 ± 150.85	985.38 ± 151.57	867.04 ± 161.92	1196.33 ± 133.63	974.77 ± 86.11	1228.50 ± 92.80	1045.25 ± 98.64	1263.80 ± 74.90

SD = standard deviation, deg/s = degrees per second

Table 8.20. Chapter 6 individual boxer peak rear leg GRF performance changes from pre-to-post intervention.

	Jab		Rear-hand cross		Lead hook		Rear hook		Lead uppercut		Rear uppercut	
Group (participant)	**Pre (N/s)**	**Post (N/s)**	**Pre (N/s)**	**Post (N/s)**	**Pre (N/s)**	**Post (N/s)**	**Pre (N/s)**	**Post (N/s)**	**Pre (N/s)**	**Post (N/s)**	**Pre (N/s)**	**Post (N/s)**
Control												
1	0.88	0.90	0.96	0.74	0.87	0.65	0.86	0.78	1.02	0.82	0.73	0.71
2	1.06	0.86	0.81	0.75	0.86	0.82	0.75	0.85	0.84	0.89	0.66	0.73
3	0.98	1.01	0.89	0.84	0.90	0.71	0.84	0.84	0.90	1.07	0.81	0.93
4	0.96	1.06	0.81	0.83	0.68	0.77	0.68	0.75	0.96	0.91	0.71	0.62
5	0.90	1.23	0.86	0.83	0.80	1.03	0.77	0.83	0.92	1.17	0.75	0.74
Mean ± SD	0.96 ± 0.07	1.01 ± 0.15	0.87 ± 0.06	0.80 ± 0.05	0.82 ± 0.09	0.80 ± 0.14	0.78 ± 0.07	0.81 ± 0.04	0.93 ± 0.07	0.97 ± 0.15	0.73 ± 0.05	0.75 ± 0.12
Strength												
1	0.94	1.21	0.77	0.99	0.78	1.19	0.70	0.90	0.74	1.06	0.68	0.75
2	0.91	1.21	0.79	0.80	0.84	1.11	0.84	0.89	0.84	1.27	0.72	1.00
3	1.21	1.73	1.08	1.23	1.02	1.29	1.01	1.05	1.30	1.42	0.97	1.30
4	0.76	1.14	0.78	0.80	0.72	0.88	0.71	0.75	0.80	1.03	0.64	1.00
5	1.07	1.70	0.94	1.03	1.14	1.53	0.85	1.00	1.12	1.31	0.74	0.71
Mean ± SD	0.98 ± 0.17	1.40 ± 0.29	0.87 ± 0.14	0.97 ± 0.18	0.90 ± 0.18	1.20 ± 0.24	0.82 ± 0.13	0.92 ± 0.11	0.96 ± 0.24	1.22 ± 0.17	0.75 ± 0.13	0.95 ± 0.24
Contrast												
1	0.82	1.23	0.83	0.99	0.81	1.52	0.81	0.95	1.10	1.64	0.87	1.16
2	0.77	1.46	0.94	1.01	0.83	0.97	1.01	0.97	1.03	1.18	0.84	1.08
3	1.08	1.90	0.88	1.26	0.92	1.39	0.92	1.03	0.99	1.44	0.78	1.19
4	0.96	1.66	0.93	0.84	1.03	1.78	0.86	0.91	1.03	1.80	0.78	1.26
5	0.90	1.70	0.77	1.47	0.73	1.93	0.68	1.04	0.89	1.52	0.62	1.21
Mean ± SD	0.91 ± 0.12	1.59 ± 0.25	0.87 ± 0.07	1.12 ± 0.25	0.86 ± 0.11	1.52 ± 0.37	0.86 ± 0.12	0.98 ± 0.05	1.01 ± 0.07	1.51 ± 0.23	0.78 ± 0.09	1.18 ± 0.07

SD = standard deviation, GRF = ground reaction force, N/s = Newtons per second

Appendix 7

Tests of Between-Subjects Effects

Dependent Variable: Squat1RMpost

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	6506.590[a]	3	2168.863	386.401	.000	.991
Intercept	147.563	1	147.563	26.290	.000	.705
Squat1RMpre	3860.757	1	3860.757	687.826	.000	.984
Group	1588.273	2	794.137	141.482	.000	.963
Error	61.743	11	5.613			
Total	213075.000	15				
Corrected Total	6568.333	14				

a. R Squared = .991 (Adjusted R Squared = .988)

Figure 8.8. Chapter 6 back squat 1RM ANCOVA between-subject effects SPSS output.

Pairwise Comparisons

Dependent Variable: Squat1RMpost

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-14.532*	1.499	.000	-18.758	-10.306
	3	-25.483*	1.522	.000	-29.775	-21.190
2	1	14.532*	1.499	.000	10.306	18.758
	3	-10.950*	1.519	.000	-15.234	-6.667
3	1	25.483*	1.522	.000	21.190	29.775
	2	10.950*	1.519	.000	6.667	15.234

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Figure 8.9. Chapter 6 back squat 1RM ANCOVA pairwise comparisons SPSS output.

Tests of Between-Subjects Effects

Dependent Variable: Bench1RMpost

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	5297.273[a]	3	1765.758	140.281	.000	.975
Intercept	29.434	1	29.434	2.338	.154	.175
Bench1RMpre	4004.240	1	4004.240	318.118	.000	.967
Group	856.413	2	428.206	34.019	.000	.861
Error	138.460	11	12.587			
Total	185399.000	15				
Corrected Total	5435.733	14				

a. R Squared = .975 (Adjusted R Squared = .968)

Figure 8.10. Chapter 6 bench press 1RM ANCOVA between-subject effects SPSS output.

Pairwise Comparisons

Dependent Variable: Bench1RMpost

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-8.461*	2.262	.010	-14.839	-2.083
	3	-18.569*	2.255	.000	-24.929	-12.209
2	1	8.461*	2.262	.010	2.083	14.839
	3	-10.108*	2.245	.003	-16.438	-3.778
3	1	18.569*	2.255	.000	12.209	24.929
	2	10.108*	2.245	.003	3.778	16.438

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Figure 8.11. Chapter 6 bench press 1RM ANCOVA pairwise comparisons SPSS output.

Tests of Between-Subjects Effects

Dependent Variable: Deadlift1RMpost

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	8440.004[a]	3	2813.335	382.865	.000	.991
Intercept	20.025	1	20.025	2.725	.127	.199
Deadlift1RMpre	4514.171	1	4514.171	614.330	.000	.982
Group	2248.762	2	1124.381	153.016	.000	.965
Error	80.829	11	7.348			
Total	353562.500	15				
Corrected Total	8520.833	14				

a. R Squared = .991 (Adjusted R Squared = .988)

Figure 8.12. Chapter 6 HBD 1RM ANCOVA between-subject effects SPSS output.

Pairwise Comparisons

Dependent Variable: Deadlift1RMpost

					95% Confidence Interval for Difference[b]	
(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
1	2	-20.381*	1.717	.000	-25.222	-15.541
	3	-29.966*	1.757	.000	-34.921	-25.011
2	1	20.381*	1.717	.000	15.541	25.222
	3	-9.585*	1.740	.001	-14.492	-4.677
3	1	29.966*	1.757	.000	25.011	34.921
	2	9.585*	1.740	.001	4.677	14.492

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Figure 8.13. Chapter 6 HBD 1RM ANCOVA pairwise comparisons SPSS output.

Tests of Between-Subjects Effects

Dependent Variable: Squat0.67post

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	12.526[a]	3	4.175	189.994	.000	.981
Intercept	.439	1	.439	19.961	.001	.645
Squat0.67pre	5.882	1	5.882	267.673	.000	.961
Group	4.316	2	2.158	98.193	.000	.947
Error	.242	11	.022			
Total	585.530	15				
Corrected Total	12.767	14				

a. R Squared = .981 (Adjusted R Squared = .976)

Figure 8.14. Chapter 6 normalised back squat 1RM ANCOVA between-subject effects SPSS output.

Pairwise Comparisons

Dependent Variable: Squat0.67post

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-.764*	.094	.000	-1.029	-.499
	3	-1.332*	.096	.000	-1.601	-1.063
2	1	.764*	.094	.000	.499	1.029
	3	-.568*	.095	.000	-.835	-.301
3	1	1.332*	.096	.000	1.063	1.601
	2	.568*	.095	.000	.301	.835

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Figure 8.15. Chapter 6 normalised back squat 1RM ANCOVA pairwise comparisons SPSS output.

Tests of Between-Subjects Effects

Dependent Variable: Bench0.67post

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	9.885[a]	3	3.295	103.964	.000	.966
Intercept	.070	1	.070	2.203	.166	.167
Bench0.67pre	6.693	1	6.693	211.176	.000	.950
Group	2.232	2	1.116	35.206	.000	.865
Error	.349	11	.032			
Total	508.935	15				
Corrected Total	10.234	14				

a. R Squared = .966 (Adjusted R Squared = .957)

Figure 8.16. Chapter 6 normalised bench press 1RM ANCOVA between-subject effects SPSS output.

Pairwise Comparisons

Dependent Variable: Bench0.67post

(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-.439*	.115	.008	-.762	-.116
	3	-.948*	.113	.000	-1.267	-.629
2	1	.439*	.115	.008	.116	.762
	3	-.508*	.113	.003	-.827	-.190
3	1	.948*	.113	.000	.629	1.267
	2	.508*	.113	.003	.190	.827

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Figure 8.17. Chapter 6 normalised bench press 1RM ANCOVA pairwise comparisons SPSS output.

Tests of Between-Subjects Effects

Dependent Variable: Hbd0.67post

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	16.393[a]	3	5.464	277.833	.000	.987
Intercept	.110	1	.110	5.612	.037	.338
Hbd0.67pre	6.506	1	6.506	330.811	.000	.968
Group	6.035	2	3.018	153.437	.000	.965
Error	.216	11	.020			
Total	975.489	15				
Corrected Total	16.609	14				

a. R Squared = .987 (Adjusted R Squared = .983)

Figure 8.18. Chapter 6 normalised HBD 1RM ANCOVA between-subject effects SPSS output.

Pairwise Comparisons

Dependent Variable: Hbd0.67post

					95% Confidence Interval for Difference[b]	
(I) Group	(J) Group	Mean Difference (I-J)	Std. Error	Sig.[b]	Lower Bound	Upper Bound
1	2	-1.059*	.089	.000	-1.311	-.807
	3	-1.566*	.091	.000	-1.824	-1.308
2	1	1.059*	.089	.000	.807	1.311
	3	-.507*	.089	.000	-.759	-.255
3	1	1.566*	.091	.000	1.308	1.824
	2	.507*	.089	.000	.255	.759

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Figure 8.19. Chapter 6 normalised HBD 1RM ANCOVA pairwise comparisons SPSS output.

Appendix 8

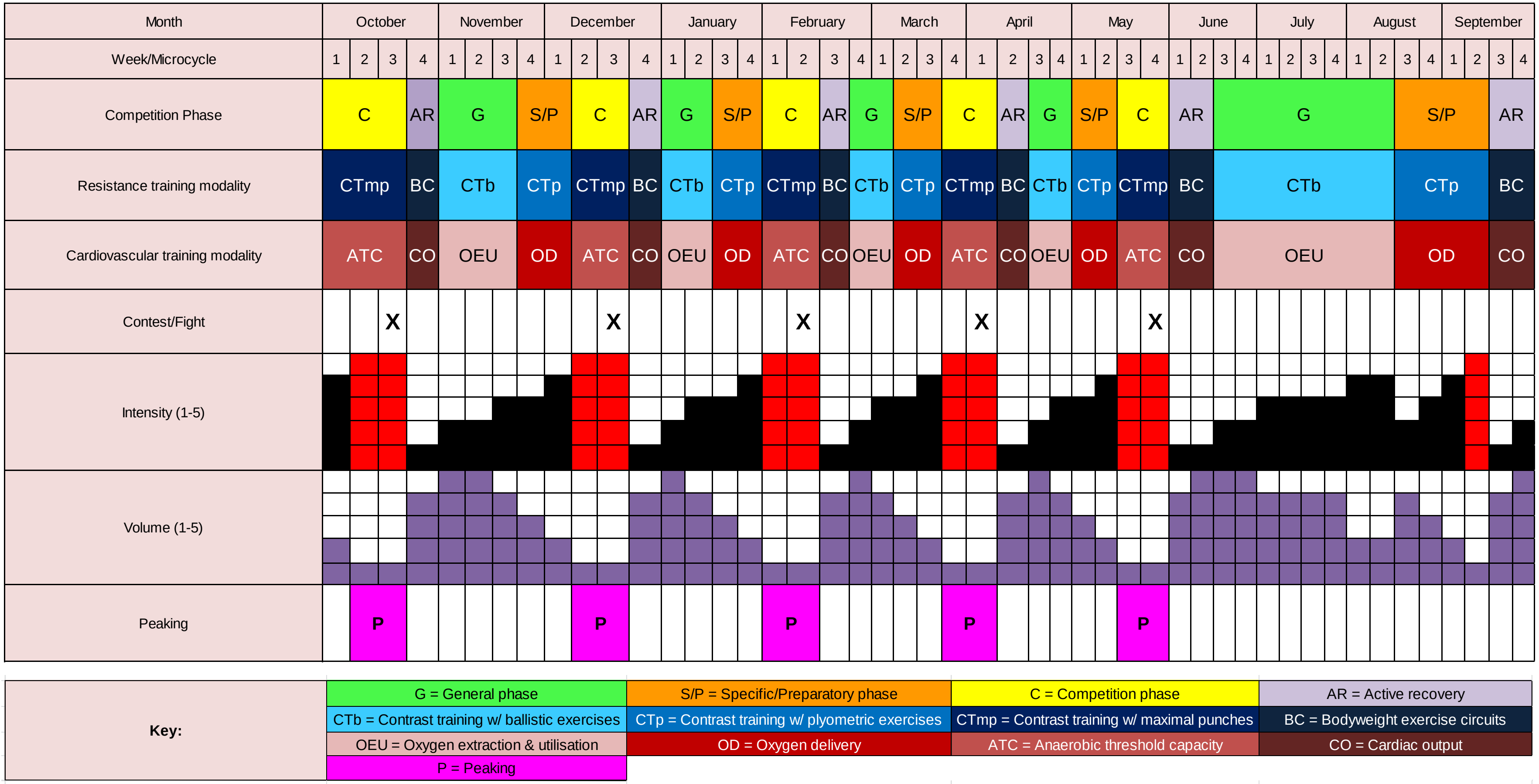

Figure 8.20. Contrast training-based annual periodised training programme model for amateur boxing.

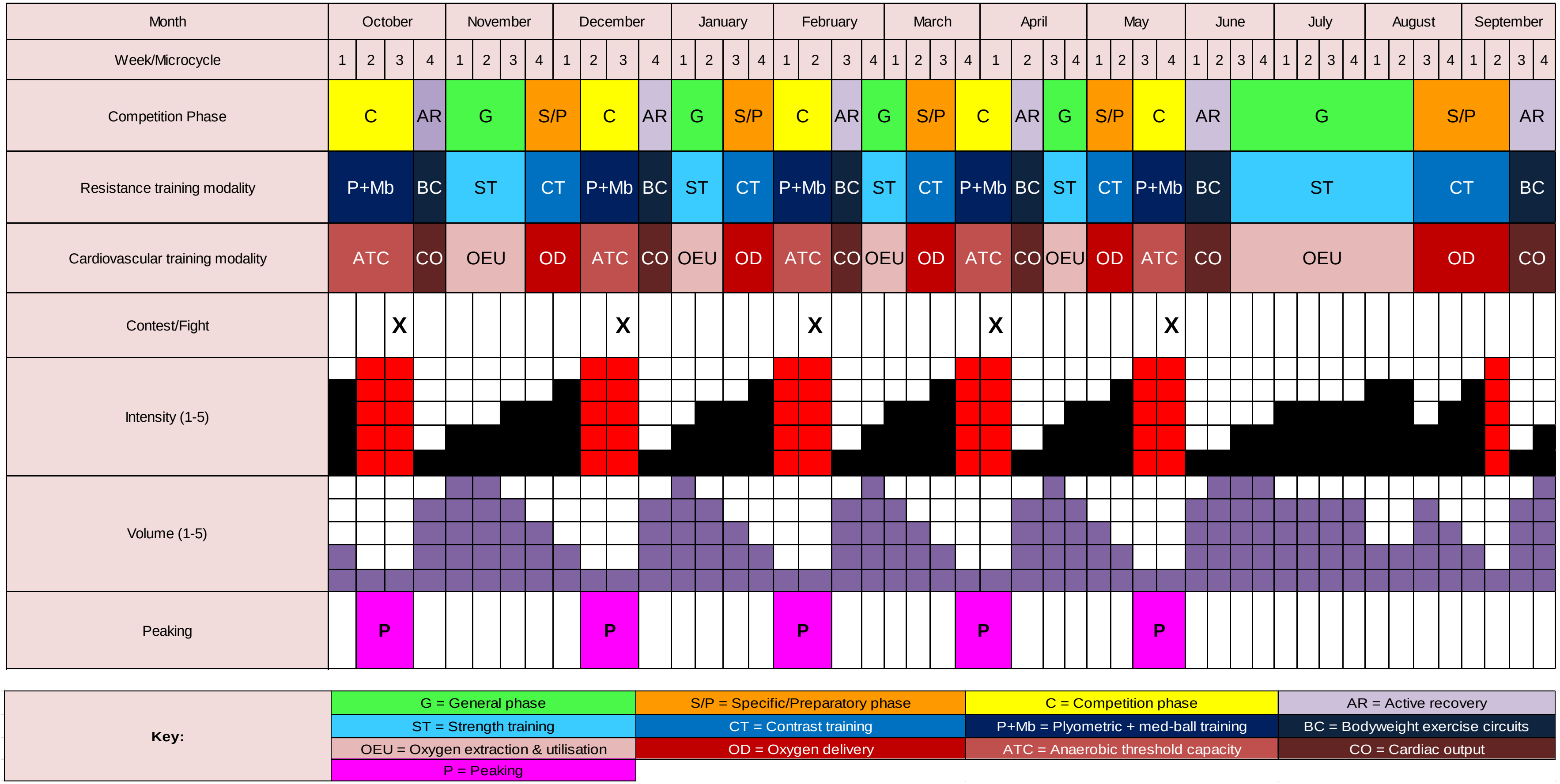

Figure 8.21. General resistance training-based periodised training programme model for amateur boxing.

Appendix 9

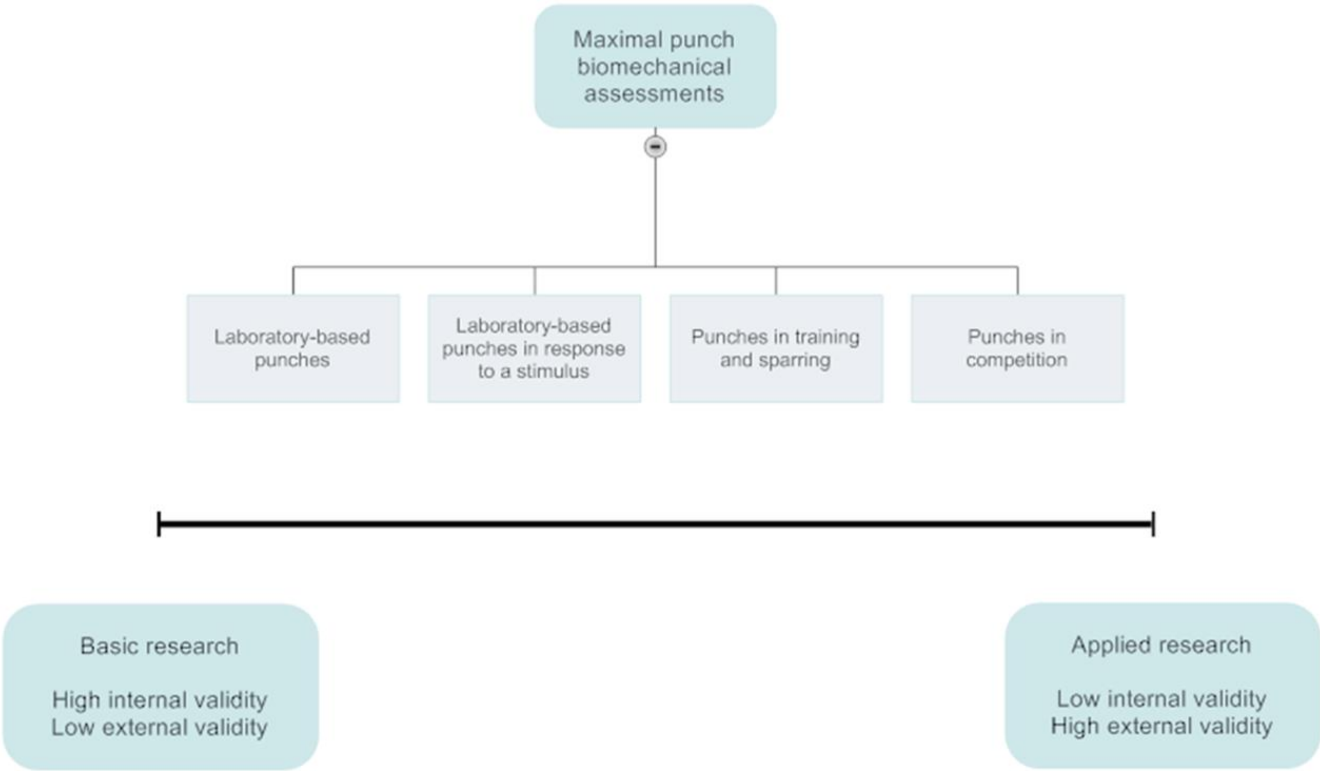

Figure 8.22. Research framework for future biomechanical assessments of maximal punches (adapted from Bridge, 2011).

Appendix 10

Figure 8.23. Title 'Gladiator Stick' boxing training device.

Figure 8.24. Example training drill using Title 'Gladiator Stick' training device.

Appendix 11

Table 8.21. Example contrast training protocols with bilateral exercises at different training phases of a 9-week boxing-specific periodised training programme.

Weeks before competition	Training phase	Exercise	Repetitions	Sets	Load	Rest period
9-7	'General'	1a. Back squat 1b. Jump squat	3 3	2 per	87.5% back squat 1RM 40% back squat 1RM	3-5 minutes between sets
		2a. Bench press 2b. Bench throw	3 3	2 per	87.5% bench press 1RM 40% bench press 1RM	
		3a. HBD 3b. HB jump	3 3	2 per	87.5% HBD 1RM 40% HBD 1RM	
6-4	'Specific/Preparatory'	1a. Back squat 1b. CMJ	2-3 3-5	2 per	90% back squat 1RM Bodyweight	3-5 minutes between sets
		2a. Bench press 2b. Ballistic push-up	2-3 3-5	2 per	90% bench press 1RM bodyweight	
		3a. HBD 3b. Standing long/broad jump	2-3 3-5	2 per	90% HBD 1RM Bodyweight	
3-1	'Competition'	1a. Back squat 1b. Maximal straight punches	1-2 3 per hand	2 per	92.5% back squat 1RM 10 oz boxing gloves	3-5 minutes between sets
		2a. Bench press 2b. Maximal hook punches	1-2 3 per hand	2 per	92.5% bench press 1RM 10 oz boxing gloves	
		3a. HBD 3b. Maximal uppercut punches	1-2 3 per hand	2 per	92.5% HBD 1RM 10 oz boxing gloves	

1RM = one-repetition maximum, HBD = hexagonal-bar deadlift, HB = hexagonal bar, CMJ = countermovement jump, MB = medicine ball.

Table 8.22. Example contrast training protocols with unilateral exercises at different training phases of a 9-week boxing-specific periodised training programme.

Weeks before competition	Training phase	Exercise	Repetitions	Sets	Load	Rest period
9-7	'General'	1a. Barbell split squat 1b. Split squat jumps	3 per side 3 per side	2 per	87.5% barbell split squat 1RM 40% barbell split squat 1RM	3-5 minutes between sets
		2a. Landmine press 2b. Landmine punch throw	3 per side 3 per side	2 per	87.5% landmine press 1RM 40% landmine press 1RM	
		3a. Reverse barbell lunge 3b. Alternating lunge jump	3 per side 3 per side	2 per	87.5% reverse barbell lunge 1RM 40% reverse barbell lunge 1RM	
6-4	'Specific/Preparatory'	1a. Barbell split squat 1b. Alternating single-leg bounds	2-3 per side 3-5 per side	2 per	90% barbell split squat 1RM Bodyweight	3-5 minutes between sets
		2a. Landmine press 2b. MB shot put	2-3 per side 3-5 per side	2 per	90% landmine press 1RM 2-4 kg	
		3a. Reverse barbell lunge 3b. Single-leg long jump	2-3 per side 3-5 per side	2 per	90% reverse barbell lunge 1RM Bodyweight	
3-1	'Competition'	1a. Barbell split squat 1b. Maximal straight punches	1-2 3 per hand	2 per	92.5% barbell split squat 1RM 10 oz boxing gloves	3-5 minutes between sets
		2a. Landmine press 2b. Maximal hook punches	1-2 3 per hand	2 per	92.5% landmine press 1RM 10 oz boxing gloves	
		3a. Reverse barbell lunge 3b. Maximal uppercut punches	1-2 3 per hand	2 per	92.5% reverse barbell lunge 1RM 10 oz boxing gloves	

1RM = one-repetition maximum, MB = medicine ball.

Appendix 12

Faculty of Life Sciences
Research Ethics Committee

frec@chester.ac.uk

13/08/2015

Edward Stanley
2 Cattonhall Cottages
Frodsham

Study title:	***An analysis of the 3D kinetics and kinematics of six single maximal punches in amateur boxing***
FREC reference:	***1101/15/ES/SES***
Version number:	***1***

Thank you for sending your application to the Faculty of Life Sciences Research Ethics Committee for review.

I am pleased to confirm ethical approval for the above research, provided that you comply with the conditions set out in the attached document, and adhere to the processes described in your application form and supporting documentation.

The final list of documents reviewed and approved by the Committee is as follows:

Document	Version	Date
Application Form	1	June 2015
Appendix 1 – List of References	1	June 2015
Appendix 2 – Summary CV for Lead Researcher	1	June 2015
Appendix 3 – Participant Information Sheet [PIS]	1	June 2015
Appendix 4 – Participant Consent Form	1	June 2015
Appendix 5 – Information sheet/letters to other personnel	1	June 2015
Appendix 6 – Written permissions from relevant personnel	1	June 2015
Appendix 7 – Risk Assessment	1	June 2015
Appendix 8 – physical Activity Readiness Questionnaire (PAR-Q)	1	June 2015
Appendix 9 – Research study timetable/order of procedures and schematic diagram	1	June 2015
Response to FREC request for further information or clarification	1	June 2015

Please note that this approval is given in accordance with the requirements of English law only. For research taking place wholly or partly within other jurisdictions (including Wales, Scotland and Northern Ireland), you should seek further advice from the Committee Chair / Secretary or the Research and Knowledge Transfer Office and may need additional approval from the appropriate agencies in the country (or countries) in which the research will take place.

With the Committee’s best wishes for the success of this project.

Yours sincerely,

Dr. Stephen Fallows
Chair, Faculty Research Ethics Committee

Enclosures: Standard conditions of approval.

Cc. Supervisor/FREC Representative

Appendix 13

Participant Information Sheet

Title of Project: An analysis of the 3D kinetics and kinematics of six single maximal punches in amateur boxers.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

What is the purpose of the study?
The purpose of this research study is to assess the kinetic (the forces that produce movement) and kinematic (the mechanics of movement) qualities of different punching techniques (jab, cross, lead hook, rear hook, lead uppercut and rear uppercut) within amateur boxing. These qualities include velocity, acceleration and ground reaction forces (GRF) that contribute to punching performance.

Why have I been chosen?
You have been chosen because you are a male amateur boxer who has at least one official bout and/or is deemed 'competent' at performing boxing techniques, having completed boxing specific-training at least twice per week at a registered boxing club for 2 or more years.

Do I have to take part?
It is up to you to decide whether to take part within the study. If you decide to take part you, will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect your rights in any way and will not be questioned.

What will happen to me if I take part?
You will complete a habituation session before the commencement of the research project to become familiar with the equipment being used, the requirements of the testing and the maximal punching techniques that will be assessed. Once completed, you will be required to perform maximal jab, rear-hand cross, lead hook, rear hook, lead uppercut and rear uppercut punches against a water-filled punching bag whilst being recorded by a 3D motion capture system. Testing will consist of one session that will last approximately 120 minutes, including warm-up, testing protocol and cool-down procedures. The testing procedure will consist of:

- Jab and rear-hand cross assessments (6 trials per punch, 60 seconds rest between trials).
- Lead and rear-hand hook assessments (6 trials per punch, 60 seconds rest between trials).

- Lead and rear-hand uppercut assessments (6 trials per punch, 60 seconds rest between trials).

No one will be identifiable in the final report and all results will be kept confidential by the lead researcher.

What are the possible disadvantages and risks of taking part?

- Slight risk of injury (due to the execution of punches performed at maximal intensity).
- Increased number of weekly training hours (if you continue with your current training/physical activity regimen).

What are the possible benefits of taking part?

- Discover personal punching kinematics and kinetics.
- Discover the velocities produced for each punch type and how force production differs between punch types.
- Possible understanding of why punching mechanics and ground reaction forces (GRF) differ between punching techniques.

What if something goes wrong?

If you wish to complain or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Dean of the Faculty of Science and Engineering, University of Chester, Parkgate Road, Chester, CH1 4BJ.

Will my taking part in the study be kept confidential?

All information which is collected about you during the course of the research will be kept strictly confidential so that only the researcher carrying out the research and the researcher's university supervisor will have access to such information. Once the research had concluded, all research results and data will be kept confidential and secured on a USB pen stick, of which will be placed within a secure location for a minimum of 10 years.

What will happen to the results of the research study?

The results will be written up into a thesis which will be subsequently submitted for my PhD in Sport and Exercise Science. Individuals who participate will not be identified in any subsequent report or publication and all data will be kept completely confidential.

Who is organising the research?

The research is conducted as part of a PhD within the Department of Sport & Exercise Sciences at the University of Chester. The study is organised with supervision from the Department, by Edward Stanley, a PhD student.

Who may I contact for further information?

If you would like more information about the research before you decide whether or not you would be willing to take part, please contact:

Edward Stanley – e.stanley@chester.ac.uk

Thank you for your interest in this research.

Appendix 14

Pre-test Questionnaire

An analysis of the 3D kinetics and kinematics of six single maximal punches in amateur boxing

Researcher*:* *Edward Stanley*

Name:_________________________________ Test date:________________

Contact number:____________________________ Date of birth:___________

In order to ensure that this study is as safe and accurate as possible, it is important that each potential participant is screened for any factors that may influence the study. Please circle your answer to the following questions:

1. Has your doctor ever said that you have a heart condition *and* that you should only perform physical activity recommended by a doctor? YES/NO
2. Do you feel pain in the chest when you perform physical activity? YES/NO
3. In the past month, have you had chest pain when you were not performing physical activity? YES/NO
4. Do you lose your balance because of dizziness *or* do you ever lose consciousness? YES/NO
5. Do you have bone or joint problems (e.g. back, knee or hip) that could be made worse by a change in your physical activity? YES/NO
6. Is your doctor currently prescribing drugs for your blood pressure or heart condition? YES/NO
7. Are you pregnant, or have you been pregnant in the last six months? YES/NO
8. Have you injured your hip, knee or ankle joint in the last six months? YES/NO
9. Do you know of any other reason why you should not participate in physical activity? YES/NO

Thank you for taking your time to fill in this form. If you have answered 'yes' to any of the above questions, unfortunately you will not be able to participate in this study.

Appendix 15

University of Chester

Participant Consent Form

Title of Project: An analysis of the 3D kinetics and kinematics of six single maximal punches in amateur boxers.

Name of Researcher: Edward Stanley

Please initial box

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason and without my legal rights being affected. ☐

3. I agree to take part in the above study. ☐

____________________	____________________	____________________
Name of Participant	Date	Signature
____________________	____________________	____________________
Researcher	Date	Signature